Saint Louis River Estuary
Clay-Influenced Bay Assessment

Pokegama Bay on a fall day. Photo by Craig Roesler, Wisconsin DNR

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About

The Saint Louis River Estuary (SLRE) is a Great Lakes Area of Concern where efforts to improve water quality, including nutrient and sediment loading reductions, have been ongoing. Some bays in the estuary were known to have substantially higher total phosphorus concentrations than the remainder of the estuary. Three bays, Allouez, Pokegama, and Kimballs, were extensively monitored for water quality and biological condition in 2017. Objectives of the monitoring were to:

- Document the current water quality and biotic conditions in these SLRE clay-influenced bays
- Determine if current nutrient and suspended solids concentrations are negatively affecting aquatic life
- Provide data that could be used to determine if site specific water quality goals are warranted

Funding

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Beneficial Use Impairment Target

BUI removal target of 30 ug/l for total phosphorus has been established for the St. Louis River portion of the AOC.

This target was established to ensure that anthropogenic sources and activities in the St. Louis River AOC do not result in excessive phytoplankton productivity and nuisance algal conditions within the St. Louis River Estuary (SLRE).

The lower St. Louis River (SLR) is part of a Great Lakes Area of Concern (AOC) (Figure 1). The SLR AOC has nine beneficial use impairments (BUI's) listed in the Remedial Action Plan (MPCA and WDNR 2017). One of the BUI's is "Excessive Loading of Sediment and Nutrients."

Diatom-inferred (DI) total phosphorus concentrations (TP's) from sediment core analyses (Reavie 2016) indicated that TP's in some SLRE bays (including Allouez and Pokegama Bays) currently exceed the TP goal (30 ug/l) for the SLRE and were at or above this goal prior to watershed development. Therefore, site specific water quality goals for these bays may be appropriate.

Three clay-influenced bays on the Wisconsin side of the SLRE were selected for monitoring: Allouez Bay, Pokegema Bay, and Kimballs Bay (Figure 2). These areas are the largest clay-influenced bays in the estuary. Limited pre-existing water quality data was available for these bays. Direct watersheds for these bays contain clay-rich soils that are highly erodible, and prone to high rates of surface runoff.

The monitoring was intended to:

- Document the current water quality and biotic conditions in these SLRE clay-influenced bays.
- Determine if current nutrient and suspended solids concentrations are negatively affecting aquatic life.
- Provide data that could be used to determine if site specific water quality goals are warranted.

The three bays were monitored during May – October of 2017 for water quality, algae, sediment chemistry, and benthic invertebrates. Tributary streams for the bays were monitored for water quality. Pre-existing water quality and biotic information was reviewed and summarized. A companion project to assess fish communities in the bays was also conducted in 2017 (Nelson 2017). A summary of that assessment is included in this report.

Bay Characteristics and Water Quality

The three bays have some unique characteristics that influence their water quality. Allouez Bay is large (1,011 acres), shallow, and subject to frequent wind-induced mixing. The mouth of the bay is adjacent to the Superior entrance to Lake Superior. Seiche-induced backflows of Lake Superior water influence the bay.

Allouez Bay had minimal thermal and dissolved oxygen stratification. There were indications that seiche-induced inputs of cooler Lake Superior water flowed along the bay bottom at times. Mean total phosphorus concentration was 85 ug/l. Mean total suspended solids concentration was 21 mg/l. Mean chlorophyll a concentration was 7.1 ug/l. Total phosphorus and total suspended solids concentrations were higher in May and October when more watershed runoff was entering the bay. Chlorophyll a concentrations were highest in June and August when watershed runoff was low and water clarity was higher.

Pokegama Bay (441 acres) has the largest direct watershed area and so is heavily influenced by Pokegama River inflow. The bay is also affected by wetlands that fringe its narrow upstream end. Pokegama Bay also had minimal thermal and dissolved oxygen stratification. Lower dissolved oxygen concentrations occurred more frequently at the surface in the upstream end of the bay, probably due largely to decomposition of organic matter in the fringe wetlands.

There may have been occasional releases of sediment phosphorus from the deeper areas in the bay. Phosphorus release from the fringe wetlands may also have occurred. Mean total phosphorus concentration was 121 ug/l. Mean total suspended solids concentration was 32 mg/l. Mean chlorophyll a concentration was 6.2 ug/l. Total phosphorus and total suspended solids concentrations were higher in May and October at the two more downstream monitoring stations when more watershed runoff was entering the bay. Total phosphorus and total suspended solids concentrations were more variable at the most upstream monitoring station which is most strongly influenced by Pokegama River inflow. Chlorophyll a concentrations were highest in July and August when watershed runoff was low and water clarity was higher.

Kimballs Bay (101 acres) is the smallest of the three bays. Steep sloped, wooded banks line the bay's perimeter. The narrowness of the bay and the high wooded banks tend to minimize wind-induced mixing. The greater mean depth (12 ft) also helps minimize mixing. The single water quality monitoring site in the bay was close to the bay mouth and strongly influenced by seiche-induced mixing of SLRE water.

Kimballs Bay had substantial thermal and dissolved oxygen stratification despite the influence of seiche-induced mixing. Sediment phosphorus release was also substantial and prolonged during July and August. Inflow from the small tributary stream appeared to be mostly flowing along the bottom of the bay and producing higher turbidities near the bottom. Mean total phosphorus concentration was 63 ug/l. Mean total suspended solids concentration was 5 mg/l. Mean chlorophyll a concentration was 7.6 ug/l. Total phosphorus concentrations were somewhat higher in May and October, and there was also a pattern of increasing total phosphorus concentrations from mid-June to early September, probably due to sediment phosphorus release. Total suspended solids concentrations were higher in May and October like the other bays. Chlorophyll a concentrations were higher in July through early September when water clarity was higher.

For the three bays, mean total phosphorus concentrations were 2-4 times higher than those found in the rest of the SLRE (Bellinger et al 2015). Mean chlorophyll a concentrations were lower than those found in the rest of the SLRE. Mean total suspended solids concentrations were lower at the Kimballs Bay site and higher at the Allouez and Pokegama Bay sites compared to the rest of the SLRE. The data is summarized below in Table 1.

Table 1. Summary of Mean Total Phosphorus, Total Suspended Solids and Chlorophyll a Concentrations

	Size (acres)	Mean Depth (ft)	Mean TP (ug/L)	Mean TSS (ug/L)	Mean Chl a (ug/L)
Allouez Bay	1,011	6	**85**	**21**	7.1
Pokegama Bay	441	5	**121**	**32**	6.2
Kimball's Bay	101	12	**63**	5	7.6
Estuary Mean	NA	NA	31	11	9.4

(bold #s indicate values higher than the estuary mean)

Bay Chlorophyll a Relationship to Other Trophic State Indices

Chlorophyll a concentrations in the three bays showed non-standard relationships to other trophic state indices (TSI) (trophic state is a water body's level of biological productivity). Chlorophyll a concentrations were only 3 -18% of what is typically found at the total phosphorus concentrations present (Carlson 1977). Water clarities (Secchi depths) are also lower than what is typically found. The poor water clarity due to suspended clay and silt is the probable reason for these altered relationships. Suspended clay and silt is controlling water clarity and the resultant lack of light availability is limiting algal growth. Lack of typical TSI parameter relationships complicate water quality goal setting since it makes it difficult to predict responses to water quality improvements.

Bay Tributary Stream Characteristics and Monitoring Results

Land use in bay tributary stream watersheds is mostly undeveloped, with 77-94% of the watersheds comprised of forest and wetland. Agricultural row crops are absent in four of the watersheds, and only account for 1.2% of the land use in the Bear Creek watershed. Grassland (pasture and hayfield) is the largest agricultural land use and comprises 1.4-20.6% of the watersheds. Streambank and bluff erosion along streams has been identified as the dominant source of fine sediment to clay plain streams. Most runoff and streamflow occurred in May, late September, and October. Total May-October 2017 precipitation was 15% above normal.

Stream dissolved oxygen concentrations were nearly all above 5 mg/l (the WI water quality standard), except for the small tributary to Kimballs Bay that had dissolved oxygen concentrations less than 5 mg/l on two dates. That site was influenced by fringe wetlands and seiche-induced backflows, which likely accounted for the higher dissolved oxygen variability.

Stream total phosphorus concentration means ranged from 106-224 ug/l. Orthophosphate concentration means ranged from 12-33 ug/l. Total suspended solids concentration means ranged from 28-106 mg/l. Watershed non-point sources of phosphorus include pasture and hayfield runoff (including the influence of manure spreading), barnyards, and septic systems. Streambank and bluff erosion along streams is not believed to be a large phosphorus source (Bahnick 1977) but is believed to be the largest source of total suspended solids.

Effluent discharged to the Pokegama River from the Village of Superior wastewater lagoons was the only point source affecting bay tributary streams. During May-October lagoon effluent was estimated to provide about 5.7% of the Pokegama River total phosphorus load and 2.8% of the river's biochemical oxygen demand load. Elevated orthophosphate concentrations in the Pokegama River were seen when stream flow was low and lagoon discharge was occurring.

Elevated concentrations of orthophosphate, ammonia, and nitrate plus nitrite concentrations occurred during low flows in Bear Creek. This may be due to residential septic system discharges. Problems with failing septic systems have been previously documented in the Bear Creek watershed.
Unusually red water was observed in Bluff Creek on one date. Runoff from the rail yard at the taconite storage facility appeared to be the likely source of the color.

Bay Sediment Characteristics

Mean clay content of sediment in all three bays (40 – 46%) was significantly higher than that found in the remainder of the central and lower SLRE, where clay content averages about 14.7% (NOAA DIVER 2018); this is not surprising given the clay rich soils in the watersheds of the bays. Additional findings are summarized below.

- Clay content of sediment (% Clay) was moderately well correlated with phosphorus concentration (R^2 = 0.75) and iron concentration (R^2 = 0.76). Iron readily attaches to the extensive bonding surfaces of clay particles and phosphorus will attach to the iron.
- Clay content was also moderately inversely correlated with % solids (R^2 = 0.43). Clay sediment tends to have a higher water content than coarser grained sediment.
- Allouez Bay sites had the highest mean, median and maximum % sand. There was an inverse correlation between site depth and % sand for the bay (R^2 = 0.73). Sediment scouring by wave action is probably removing finer sediments at shallow sites and leaving more sand.
- Soft sediment thickness ranged from 0.9 to 12.9 feet. Water depth and soft sediment thickness showed moderate correlations for individual bays (Allouez Bay (less site ASD), R^2 = 0.42; Pokegama Bay, R^2 = 0.70). Deeper sites tend to favor long term sediment deposition.

Algae

Total algal cell densities were highest in all bays in July, August, and September. Pokegama Bay had the highest total cell density on July 10th (10,343 cells/ml). All algal phyla occurred in higher densities during those three months. Total suspended solids concentrations and turbidity were lower during these months which increased light availability for algal growth. Water temperatures were higher during these months which can also promote algal growth.

Benthic Invertebrates

The trimetric index (TMI) (Angradi et al 2016) is an index of benthic invertebrate community quality and was developed specifically for the SLRE. Allouez and Pokegama Bays were excluded from the SLRE for the development of the TMI and the accompanying ephemerid density index. However, they are still the most useful benthic invertebrate indices to apply to these bays and provide a basis of comparison to the rest of the SLRE.

The median TMI value for Allouez Bay was poor, for Pokegama Bay was fair, and for Kimballs Bay was poor. The quality of the benthic invertebrate community in all three bays was below average in comparison to the rest of the SLRE. The physical characteristics of sediment with high clay content (and corresponding high-water content) may be restrictive to some benthic invertebrates in all three of the bays, and possibly account for the low TMI values. Periods of anoxia at two sites in Kimballs Bay probably also contributed to the poor median TMI there.

The median ephemerid (mayflies) density index value (Angradi et al. 2016) for Allouez Bay was good, for Pokegama Bay was excellent, and for Kimballs Bay was poor. Median values for Allouez and Pokegama Bays were above average in comparison to the rest of the SLRE. High clay content of sediment does not appear to negatively affect ephemerid species. Periods of anoxia at two sites in Kimballs Bay may have again accounted for the poor median value there.

Aquatic Macrophytes

Results from recent aquatic macrophyte surveys (2004-2015) are available for the three bays (Danz et al. 2017) and are summarized below in Table 2:

Table 2. Aquatic Macrophyte Survey Data for the Bays

	Allouez Bay	Kimballs Bay	Pokegama Bay	All SLRE surveys
Number of species	155	74	148	NC**
Species per plot	8.8	5.0	5.8	NC**
Mean C* value	5.6	3.6	5.4	5.06

*C = coefficient of conservatism, an index of tolerance to disturbance. **NC = not comparable; number of species and species per plot are influenced by size of area surveyed and survey methods, so do not offer a simple means of comparison.

Mean C values for Allouez and Pokegama Bays are better than the mean C value for all SLRE aquatic macrophyte surveys, while the mean C value for Kimballs Bay is poorer. Allouez Bay appears to have the best aquatic plant community, while Kimballs Bay has the poorest.

Wetlands[1]

Recent wetland monitoring data (2011-2017) is available for all three bays from the Great Lakes Coastal Wetland Monitoring Program (Brady 2018).

Wetland nutrient, turbidity, and chlorophyll concentrations were generally similar to those found at open water sampling sites in 2017, although Kimballs Bay total phosphorus concentrations were higher than open water concentrations, suggesting wetland phosphorus release may be occurring at higher rates there.

Daytime dissolved oxygen concentrations in wetlands were below 3 mg/l for a significant percentage of measurements (5-25%), with Kimballs Bay having the highest percentage of such measurements. Less water mixing in Kimballs Bay due to its sheltered nature may account for these differences.
Wetland macroinvertebrate IBI's are available for Allouez and Pokegama Bays for 2011 and 2012. Allouez Bay scores were rated as moderately impacted. Pokegama Bay scores were rated as moderately impacted to most pristine.

Wetland fish IBI ratings for the four years monitored for Allouez Bay ranged from moderately impacted to mildly degraded. The rating for the one year monitored for Kimballs Bay was moderately degraded. The rating for the one year monitored for Pokegama Bay was mildly impacted.

Wetland bird and frog survey results (2012-2013) are available for Allouez and Pokegama Bays (Tozer 2014). Additional wetland bird and frog survey result are available for one or more years during 2014 - 2017 for all three bays (Brady 2018).

For the 2012-2013 bird surveys, Allouez Bay had an index of biotic integrity (IBI) score of 31.8 (fair) which is slightly below the median score of 33.3 found for 14 Lake Superior coastal wetlands (mostly outside of the SLRE). Pokegama Bay had a score of 34.0 (fair) which is slightly above that median score. For Allouez Bay, three wetland bird surveys (2014, 2016, 2017) had a median index of ecological condition (IEC) rating of high quality. A Kimballs Bay survey (2016) had an IEC rating of degraded. A Pokegama Bay survey (2016) had an IEC of mildly impacted.

For the 2012-2013 frog surveys, Allouez Bay had an IBI score of 60.0 (rated good) which is below the median score of 86.5 found for 13 Lake Superior coastal wetlands (mostly outside of the SLRE). Pokegama Bay had a score of 70.3 (rated very good) which is also below that median score.
For Allouez Bay, three wetland frog surveys (2014, 2016, 2017) had a median IEC rating of reference condition. A Kimballs Bay survey (2016) had an IEC rating of moderately degraded. A Pokegama Bay survey (2016) had an EIC rating of moderately impacted.

[1] also see Biological Indicators Summary, below

Fishery

Bay fisheries were monitored during 2017 using gill nets and shoreline electrofishing (Nelson 2018). Results are summarized in Table 3 below.

Table 3. Bay Fish Data Summary with Comparison to MN DNR Gill Net Data

Gill Net Data	Allouez Bay	Kimballs Bay	Pokegama Bay	21 MN SLRE gill net sites
Total number of species	12	6	9	19
Median number of species/net lift	9	3	9	8
Mean fish/net lift	39.9	3.6	19.3	27.5
Mean kg fish/net lift	21.9	1.3	8.3	13.0
Gill Net plus Electrofishing Data				
Total number of species	22	15	21	not applicable
Number of native species	18	14	16	not applicable
Number of non-native species	4	1	5	not applicable
Number of intolerant species	4	4	3	not applicable

Allouez and Pokegama Bays gill net data is generally similar to data collected by the Minnesota DNR during 2017 from 21 SLRE gill net sites for median number of species/net lift, mean fish/net lift, and mean kg of fish/net lift. Kimballs Bay gill net data is substantially lower than the Minnesota DNR data for those parameters.

Conclusions of the fishery survey report included, "Despite turbid conditions that may lead to the perception of poor water quality or habitat, locally popular sport fish species like walleye, northern pike, black crappie, and yellow perch were well represented in both Allouez and Pokegama Bays. Other species of interest to anglers and state fisheries management agencies were also found in these bays including lake sturgeon, muskellunge, bluegill, and channel catfish. While Increased turbidity in Allouez and Pokegama Bays may influence the presence or abundance of specific species, it has not diminished the fishery value or eliminated desirable gamefish species from these areas." (Nelson 2018)

Biological Indicators Summary

The available biological indicators for the three bays are summarized below in Table 4.

Table 4. SLRE Bays Biological Indicators

BIOLOGICAL COMMUNITY	INDICATOR	ALLOUEZ BAY	KIMBALLS BAY	POKEGAMA BAY
Benthic invertebrates	Trimetric index[1]	median = poor (poorer than average for SLRE)	median = poor (poorer than average for SLRE)	median = fair (poorer than average for SLRE)
Ephemerid mayflies	Ephemerid density index[1]	median = good (better than average for SLRE)	median = poor (poorer than average for SLRE)	median = excellent (better than average for SLRE)
Aquatic macrophytes	Species richness[2]	155	74	148
Aquatic macrophytes	Species richness per plot[2]	8.8	5.0	5.8
Aquatic macrophytes	Mean C value[2]	5.6; species that tolerate moderate disturbance; better than SLRE mean value of 5.06	3.6; generalist species that are tolerant of disturbance; poorer than SLRE mean value of 5.06	5.4; species that tolerate moderate disturbance; better than SLRE mean value of 5.06
Bay fish	multiple[6,7]; no applicable IBI available	Number fish/gill net lift = 145% of 21 site SLRE mean; kg fish/gill net lift = 168% of 21 site SLRE mean; number species /gill net lift = 112% of 21 site SLRE median; % native species = 92%; number of intolerant species = 4; "...popular sport fish species...are well represented in Allouez ...Bay."	Number fish/gill net lift = 13% of 21 site SLRE mean; kg fish/gill net lift = 10% of 21 site SLRE mean; number species /gill net lift = 38% of 21 site SLRE median; % native species = 99%; number of intolerant species = 4	Number fish/gill net lift = 70% of 21 site SLRE mean; kg fish/gill net lift = 63% of 21 site SLRE mean; number species/gill net lift = 112% of 21 site SLRE median; % native species = 79%; number of intolerant species = 3; "...popular sport fish species ... are well represented in ... Pokegama Bay."

Table 4. SLRE Bays Biological Indicators (Cont.)

BIOLOGICAL COMMUNITY	INDICATOR	ALLOUEZ BAY	KIMBALLS BAY	POKEGAMA BAY
Wetland Macroinvertebrates	Wetland macroinvertebrate IBI[4]	2011, 2012 = moderately impacted; not enough non-clay influenced SLRE surveys to allow comparison.	IBI not available	2011, 2012 median = mildly impacted; not enough non-clay influenced SLRE surveys to allow comparison.
Wetland Vegetation	Wetland vegetation IBI[4]	2011-2017 median = moderately impacted = median for non-clay influenced SLRE surveys	2014, 2016 = moderately degraded, which is poorer than the median for non-clay influenced SLRE surveys (moderately impacted).	2011, 2012, 2016 median = moderately impacted = median for non-clay influenced SLRE surveys
Wetland Fish	Wetland fish IBI[4]	2011-2017 median = moderately impaired to moderately degraded, which is slightly poorer than the median for non-clay influenced SLRE surveys (moderately impaired).	2014 = moderately degraded, which is poorer than the median for non-clay influenced SLRE surveys (moderately impaired).	2012 = mildly impacted, which is better than the median for non-clay influenced SLRE surveys (moderately impaired).
Wetland Birds	Bird IBI[3]	31.8; fair - just below median value of 33.3 found for 14 Lake Superior coastal wetlands, mostly outside of SLRE	no data	34.0; fair - just above median value of 33.3 found for 14 Lake Superior coastal wetlands, mostly outside of SLRE
Wetland Birds	Bird IEC[4]	2014 2016, 2017 median = high quality, which is better than the median for non-clay influenced SLRE surveys (moderately impacted)	2016 = degraded, which is poorer than the median for non-clay influenced SLRE surveys (moderately impacted)	2016 = mildly impacted, which is better than the median for non-clay influenced SLRE surveys (moderately impacted)
Wetland Frogs	Frog IBI[3]	60.0; good - below median value of 86.5 found for 13 Lake Superior coastal wetlands, mostly outside of SLRE	no data	70.3; very good - below median value of 86.5 found for 13 Lake Superior coastal wetlands, mostly outside of SLRE
Wetland Frogs	Frog IEC[4]	2014 2016, 2017 median = reference condition, which is better than the median for non-clay influenced SLRE surveys (mildly impacted)	2016 = moderately degraded, which is poorer than the median for non-clay influenced SLRE surveys (mildly impacted)	2016 = moderately impacted, which is poorer than the median for non-clay influenced SLRE surveys (mildly impacted)

[1]Angradi, TR, Bartsch, WM, Trebitz, AS, Brady, VJ, Launspach, JJ. 2016. A depth-adjusted ambient distribution approach for setting numeric removal targets for a Great Lakes Area of Concern beneficial use impairment: degraded benthos. J Great Lakes Res.
[2]data from Danz, et al. 2017 (get full reference)
[3]Tozer, D. 2014. LSRI nearshore monitoring project: 2012-2013 bird and frog indices of biotic integrity. EPA assistance no. GL00E00500-0.
[4]Uzarski, DG, et al. 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands (37:15).
[6]Nelson, A. 2018. St. Louis River Bays – Douglas County; 2017 fish community survey. Wisconsin Dept. of Natural Resources, Superior, WI. Unpublished report.
[7]Pinkerton, J. 2018. Personal communication. Minnesota Dept. of Natural Resources fisheries specialist, Duluth, MN.

Allouez and Pokegama Bays both had high turbidities and total phosphorus concentrations. However, biological indicators for these bays tended to have moderate values that were often close to average, and in some cases above average ((ephemerid mayflies, aquatic macrophyte mean C, wetland birds, wetland fish (Pokegama only), wetland frogs (Allouez only)) for the SLRE or other comparable sites. Current water quality conditions do not appear to be having any strong negative effect on biological communities in these two bays. This finding is similar to that of the Red Clay Project conducted during the 1970's (EPA 1980). A conclusion of that project was, "Analysis of areas of Lake Superior and the Nemadji River system which are turbid throughout the year due to erosion of unconsolidated glacial lake deposits indicated that any direct physical effects of this turbidity and resultant low-level sedimentation (on aquatic life) are minimal."

The trimetric index for benthic invertebrates is one biological indicator that is below the SLRE average for Allouez and Pokegama Bays. This may be due to the high clay and water content of the bay sediment, which could be physically restrictive to some benthic organisms.

Kimballs Bay consistently has the poorest values for the biological indicators. Kimballs Bay has the lowest turbidities and total phosphorus concentrations of the three bays. It has a very small direct clay rich soil watershed and no known legacy contaminants. The poorer biological conditions were probably naturally occurring and resulted from the bay's physical characteristics. The bay is narrow and has tall, steep wooded banks that minimize wind-induced mixing. The bay also has steeper bottom contours and greater average depth. The limited mixing results in low summer dissolved oxygen concentrations occurring at depth in the bay. Low summer dissolved oxygen concentrations have also been observed to occur more frequently in the wetlands of this bay than in Allouez and Pokegama Bays, probably also due to the limited mixing.

Low dissolved oxygen concentrations could be impairing the benthic invertebrate, ephemerid mayfly, wetland macroinvertebrate, wetland and bay fish, and possibly frog communities in Kimballs Bay. It is unclear what may be causing the poor biological indicator values for aquatic macrophytes, wetland vegetation, and wetland birds.

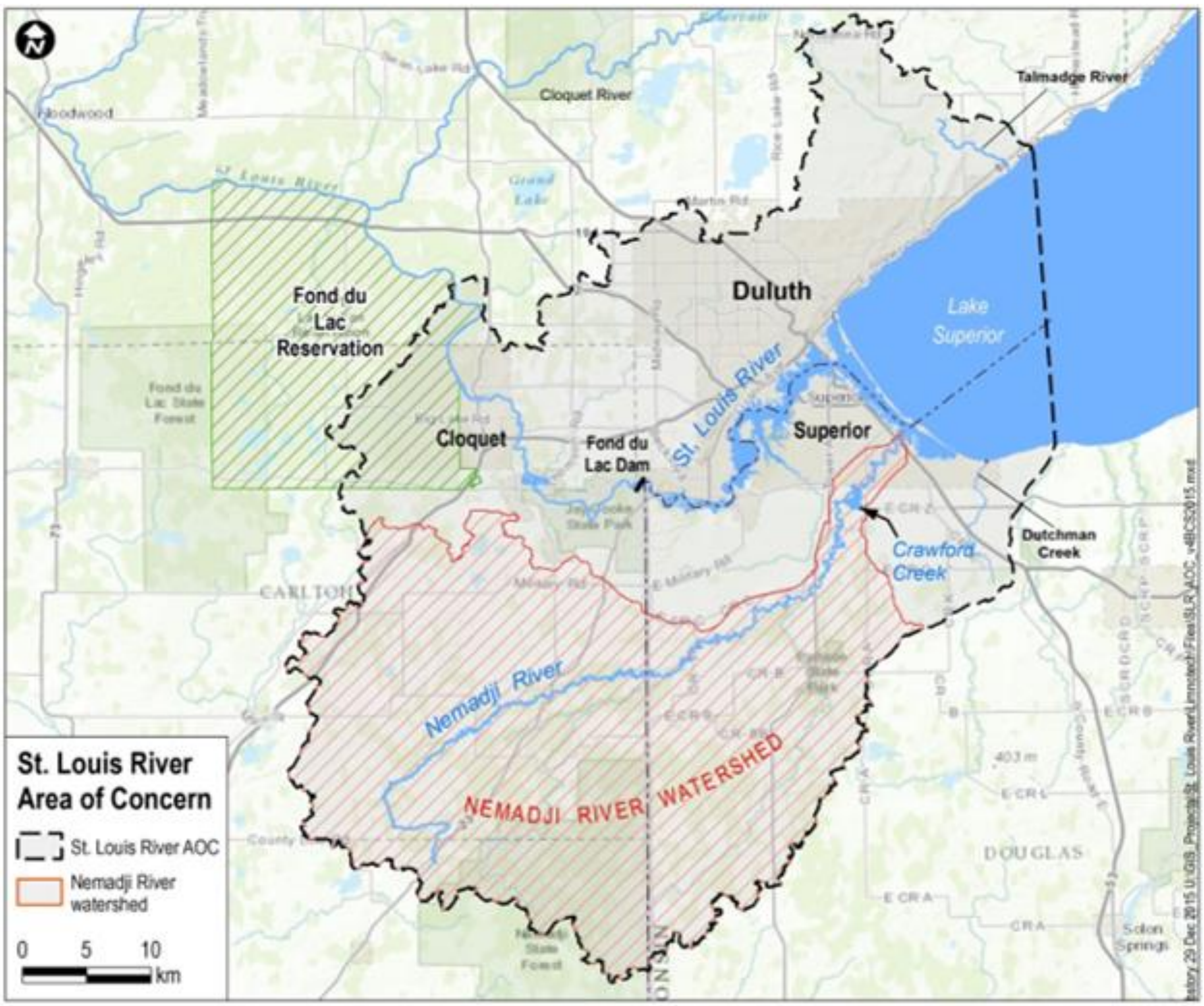
Background

The lower St. Louis River (SLR) is part of a Great Lakes Area of Concern (AOC) (Figure 1). The SLR AOC has nine beneficial use impairments (BUI's) listed in the 2016 Remedial Action Plan (MPCA and WDNR 2017). One of the BUI's is "Excessive Loading of Sediment and Nutrients."

Excessive Loading of Sediment and Nutrients Targets

- A BUI removal target of 30 ug/l for total phosphorus has been established for the St. Louis River portion of the AOC. This target was established to ensure that anthropogenic sources and activities in the St. Louis River AOC do not result in excessive phytoplankton productivity and nuisance algal conditions within the St. Louis River Estuary (SLRE).
- BUI removal targets of 15 mg/l for total suspended solids and 10 ug/l for chlorophyll a have also been established for the St. Louis River portion of the AOC (MPCA and WDNR 2013).

Figure 1. St. Louis River Area of Concern



Diatom-inferred (DI) total phosphorus concentrations (TP) from sediment core analyses (Reavie 2016) indicate that TP's in three sampled SLRE bays currently exceed the TP goal (30 ug/l) for the SLRE (Table 5). The three bays sampled were North Bay, Pokegama Bay, and Allouez Bay.

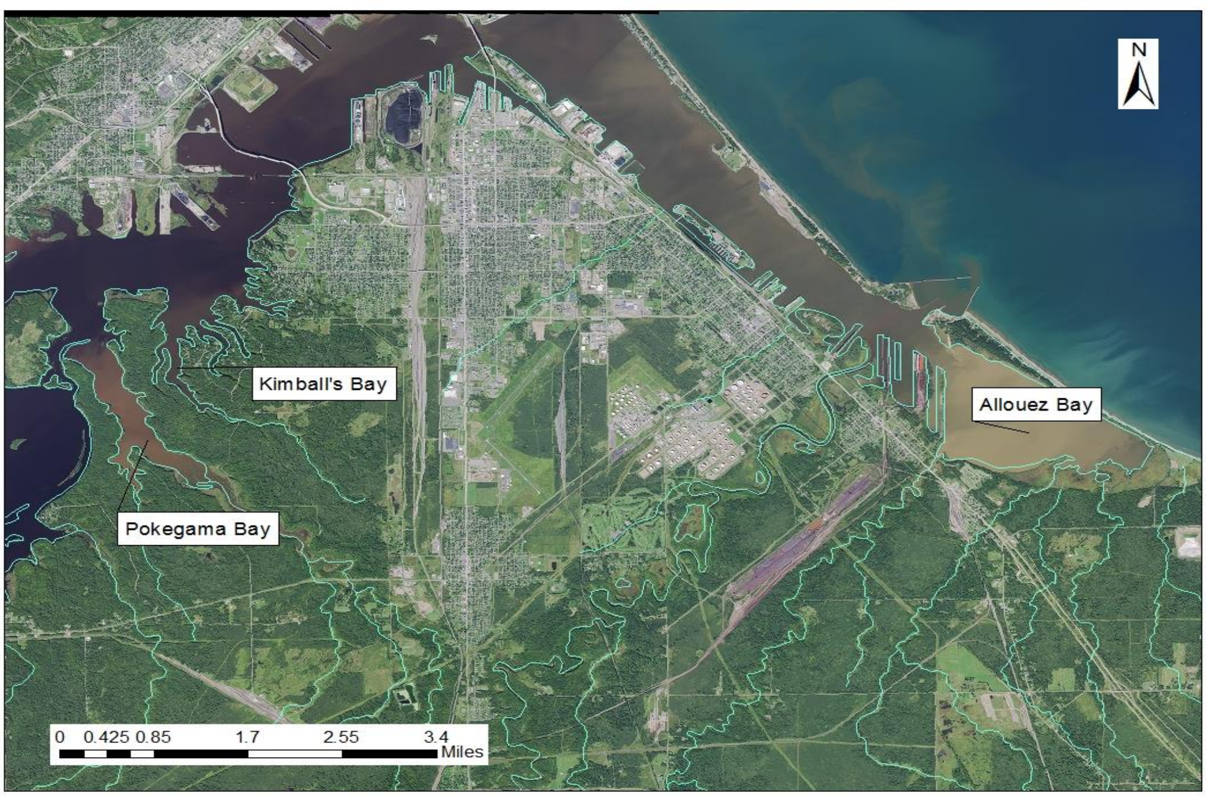
Table 5 Diatom-Inferred TP Concentrations from Sediment Cores

Site	Pre-development DI-TP (ug/l)	Recent DI-TP (ug/l) ~~(2017)~~ delete year
North Bay (MN)	40	60
Pokegama Bay (WI)	47	74
Allouez Bay (WI)	29.5	73

Pre-development DI-TP's are nearly at or above the 30 ug/l goal, so site-specific water quality targets for these bays may be appropriate. Three bays on the Wisconsin side of the SLRE were selected for monitoring (Figure 2. Allouez, Pokegema, and Kimballs Bay). Limited pre-existing water quality data was available for these bays. Direct watersheds for these bays contain clay-rich soils that are highly erodible, and prone to high rates of surface runoff. The sheltered nature of these bays provides some limitations to mixing with SLRE water. The monitoring was intended to:

- Document the current water quality and biotic conditions in these SLRE clay-influenced bays.
- Determine if current nutrient and total suspended solids concentrations are negatively affecting aquatic life.
- Provide data that could be used to determine if site specific water quality goals are warranted.

Figure 2. Monitored Bay Locations within the St. Louis River Estuary



Description of Study Area

High levels of clay turbidity in Pokegama and Allouez Bays and moderate levels in portions of Kimballs Bay can commonly be seen in air photos (Figure 2 above). An aquatic habitat classification system for the SLRE (SLRCAC 2002) classifies Pokegama and Kimballs Bay as clay-influenced river mouths, and classifies Allouez Bay as a clay-influenced bay.

All three bays are influenced by Lake Superior seiches. Periodic seiche flows of about 8 hr. duration and weak semi-diurnal tides cause flow reversals and daily variation in water height in the SLRE of about 13 cm. (Trebitz 2006). Bay and watershed physical characteristics are shown in Table 6.

Table 6. Bay and Watershed Physical Characteristics

Bay	Open Water Area (Acres)	Adjoining Wetland (Acres)	Maximum Depth (ft)	Mean Depth (ft)	Direct Watershed Area (km2)	Watershed to Open Water Ratio	May-Oct Bay Volumes Delivered by Direct Watershed
Allouez	1,011	235	16.6	6	82.4	20.1	2.3
Kimballs	101	6	16.3	12	5.63	13.8	0.8
Pokegama	441	66	10.5	5	89.3	50.0	6.9

Allouez Bay is the largest of the three bays and has the largest area of adjoining wetland. The north shore of the bay is a Lake Superior barrier beach comprised of very sandy soil. The large, open bay can be strongly influenced by wind-induced waves and mixing. The mouth of the bay is adjacent to the Superior entry to Lake Superior. The bay is influenced by seiche-induced backflows of water from Lake Superior and the St. Louis River estuary.

Nearly all of Allouez Bay has water depths ranging from 4 to 8 ft. There is a 35-acre dredged hole near the south side of the bay (at monitoring site ASD) with deeper water, around 16.6 ft. There are also deeper dredged areas at the docking slip and the access channel to the docking slip at the first pier at the mouth of the bay.

Kimballs Bay is the smallest of the three bays and has the least adjoining wetlands. Steep sloped, wooded banks line the bay’s perimeter. The narrowness of the bay and the high wooded banks tend to minimize wind-induced mixing. It has a small direct watershed (5.63 km^2) and the lowest watershed to open water ratio (13.8) of the three bays. Bottom contours also have relatively high gradients in this bay. Most of the bay has water depths greater than 9 ft. The single monitoring site in the bay is close to the bay mouth and strongly influenced by seiche-induced mixing of SLRE water.

Pokegama Bay has the largest direct watershed area (89.3 km2), and the highest watershed to open water ratio (50.0) of the three bays. Most of the adjoining wetlands are located near the upstream end where the bay is narrower and more readily influenced by the wetlands. Most of Pokegama Bay has water depths less than 6 ft. Areas greater than 6 ft are found in the downstream third of the bay and in portions of the south arm of the bay. The maximum depth is 10.5 ft.

Methods

Bay Water Quality Monitoring

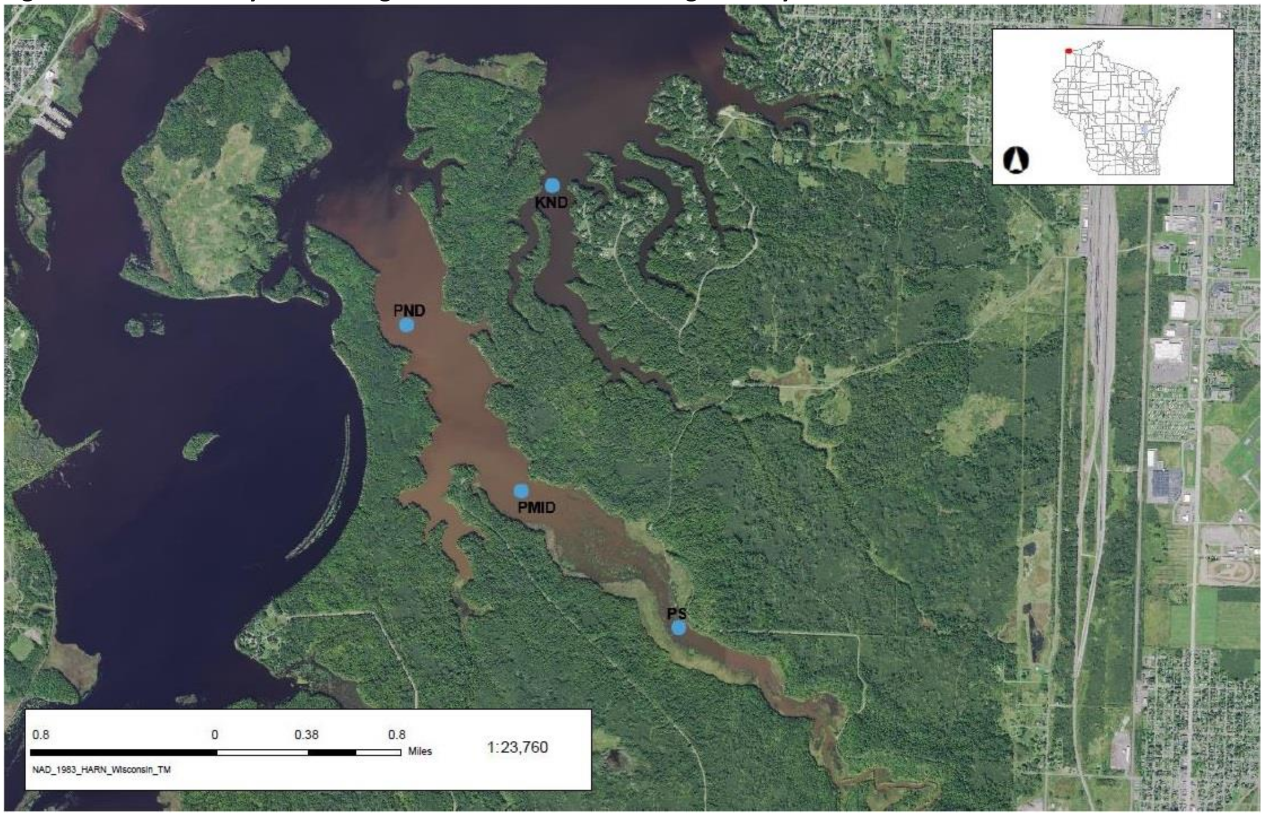
Bay water quality monitoring was conducted at three sites in Allouez Bay, one site in Kimballs Bay, and three sites in Pokegama Bay (Figures 3 and 4). The deepest site in each bay was selected as one monitoring location. Two additional sites were selected in both Allouez and Pokegama Bay, so that each of the three monitoring sites were approximately centered in an equal-sized area of the bay.

Monitoring was conducted twice per month from May through October. Water samples were collected with a 2.2-liter acrylic Kemmerer sampler at 0.5 m (1.6 ft) below the surface, and 0.5 m above the bottom. Samples were acidified, as needed, and kept on ice in the field. Dissolved total Kjeldahl nitrogen samples were field filtered. Algae samples were preserved with 1.5% glutaraldehyde. Duplicates were collected for 10% of samples. Samples were shipped on ice on the day of collection to the Wisconsin State Lab of Hygiene (except algae samples). Lab analyses included:

- Total phosphorus (EPA 365.1)
- Orthophosphate (SM4500-PE)
- Total Kjeldahl nitrogen (EPA 351.2)
- Dissolved total Kjeldahl nitrogen (EPA 351.2)

Figure 3. Water Quality Monitoring Sites in Allouez Bay

Figure 4. Water Quality Monitoring Sites in Kimballs and Pokegama Bays



- Ammonia nitrogen (EPA 350.1)
- Nitrate plus nitrite nitrogen (EPA 353.2)
- Total suspended solids (SM2540D)
- Volatile suspended solids (SM2540E)
- Turbidity (SM2130B)
- Chlorophyll a (EPA 445)

Near bottom samples were only analyzed for total phosphorus, orthophosphate, and ammonia. One shallow site in Pokegama Bay (PS; Figure 4) did not have near bottom samples collected.
Preserved algae samples were shipped on ice on the day of collection to UW-Oshkosh for analysis by Dr. Robert Pillsbury. Algae were identified to species when possible and cell densities were determined (Pilllsbury 2017).

A YSI ProDSS multiparameter meter was used for field measurements of temperature, dissolved oxygen, pH, conductivity (specific conductance), and turbidity. The meter was calibrated daily for dissolved oxygen and pH, and monthly for conductivity and turbidity. Field measurements were made 0.3 m (1 ft) below the surface, 0.3 m above the bottom, and usually at 0.6 m (2ft) intervals in between. A standard black and white Secchi disk was used for water clarity measurements.

Bay Sediment Monitoring

Bay sediment monitoring was conducted at eight sites in Allouez Bay, three sites in Kimballs Bay, and eight sites in Pokegama Bay (Figures 5 and 6). Sites included the water quality monitoring sites and additional sites that were selected to be representative of the common depth ranges in the bays. Sediment samples were collected in August or September. A stainless-steel petite Ponar grab was used for sample collection. Samples were kept on ice in the field, then refrigerated until being shipped to the lab. Duplicates were collected for 10% of samples. Samples were shipped on ice to the Wisconsin State Lab of Hygiene. Lab analyses included:

- % Solids (EPA 160.3)
- Total organic carbon (EPA 9060A)
- Phosphorus (SW846 6010B)
- Total Kjeldahl nitrogen (QuickChem 13-107-06-2-D)
- Ammonia nitrogen (QuickChem 12-107-06-1-A)
- Nitrate plus nitrite nitrogen (QuickChem 13-107-06-2-D)
- Iron (SW846 6010B)
- % Sand, silt, and clay (Hydrometer method)

Soft sediment thickness was measured by probing with ¾ inch (19 mm) diameter steel pipe.

Figure 5. Sediment and Benthic Invertebrate Monitoring Sites in Allouez Bay

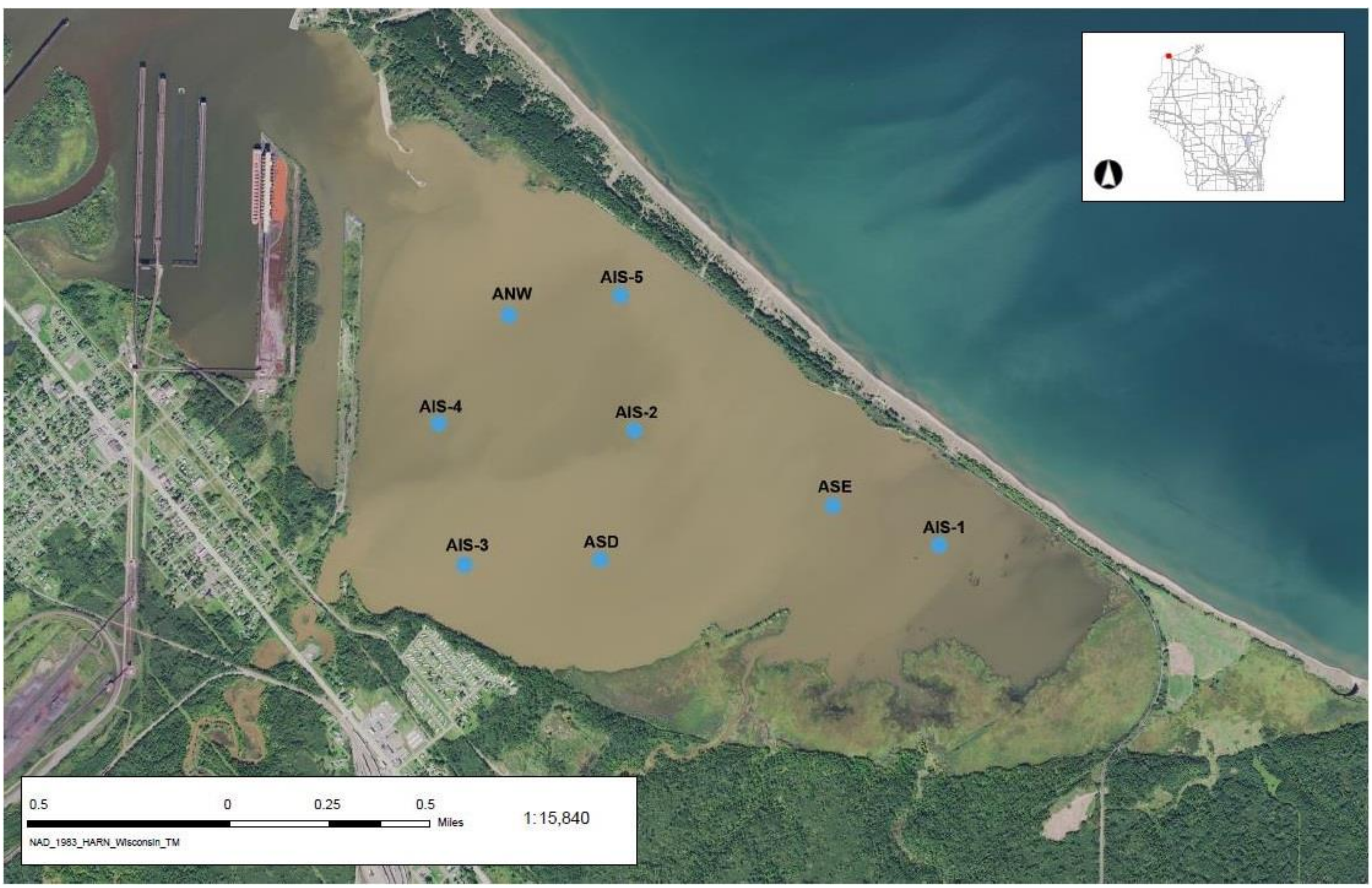
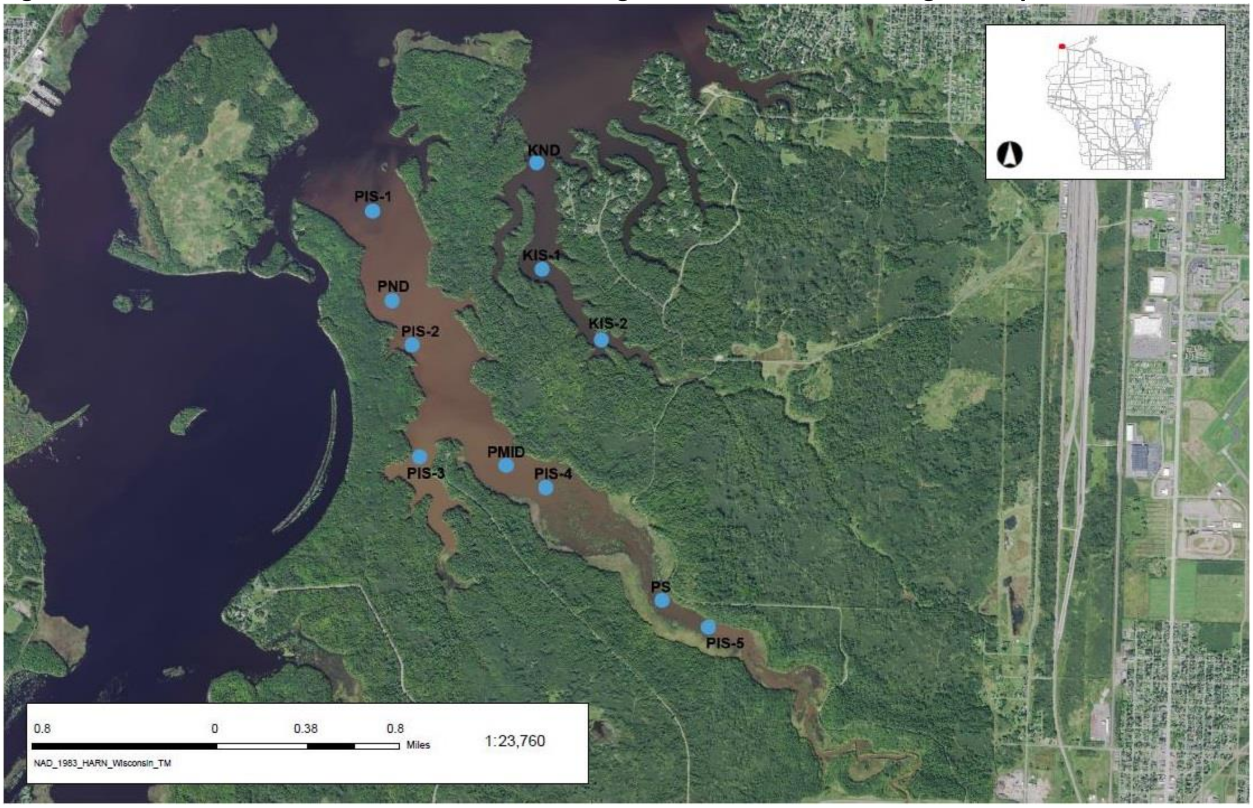


Figure 6. Sediment and Benthic Invertebrate Monitoring Sites in Kimballs and Pokegama Bays



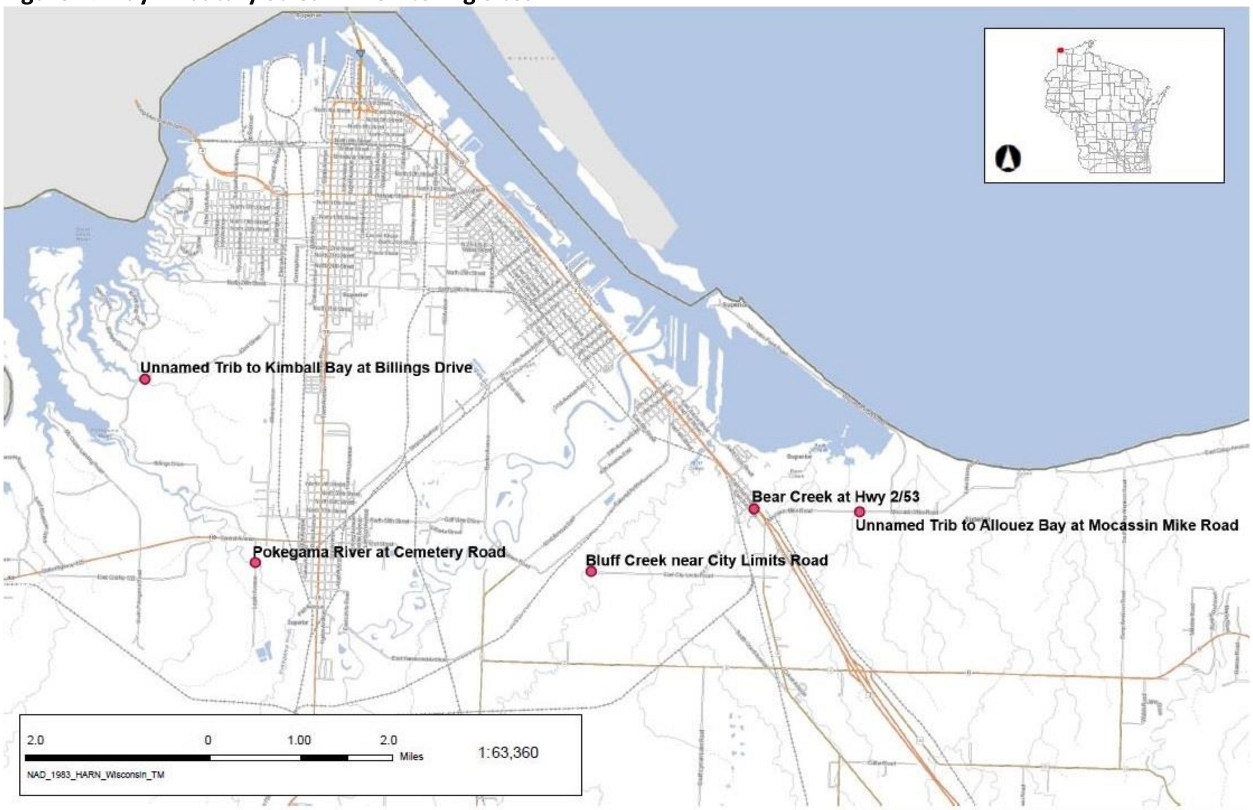
Bay Benthic Invertebrate Monitoring

Benthic invertebrate samples were collected at the same sites as sediment samples (Figures 5 and 6). Samples were collected during August 21st - 22nd. A stainless-steel petite Ponar grab was used for sample collection. Samples were washed of fine sediment using a 250-um screen bottomed bucket, and then preserved with a 10% buffered formalin solution. Duplicates were collected for 10% of samples. Samples were hand delivered to UW-Superior for analysis by Dr. Kurt Schmude using methods that have been commonly used for SLRE benthic invertebrate samples (Schmude 2010).

Bay Tributary Stream Water Quality Monitoring

Tributary stream water samples were collected during May through October at five sites (Figure 7). For the three larger, named tributary streams (Bear Creek, Bluff Creek, Pokegama River), samples were collected four times per month. Sampling was targeted to dates with higher flows, to better represent the total volume of flow. For the two smaller unnamed tributary streams, samples were collected once per month. Grab samples were collected directly in sample bottles at most sites. Due to access limitations, for the Pokegama River and the unnamed tributary to Kimballs Bay, a 2.2-liter acrylic Kemmerer sampler was used to collect samples 0.5 m (1.6 ft) below the surface.

Figure 7. Bay Tributary Stream Monitoring Sites



Samples were acidified, as needed, and kept on ice in the field. Duplicates were collected for 10% of samples. Samples were shipped on ice on the day of collection to the Wisconsin State Lab of Hygiene. Lab analyses included:

- Total phosphorus (EPA 365.1)
- Orthophosphate (SM4500-PE)
- Total Kjeldahl nitrogen (EPA 351.2)
- Ammonia nitrogen (EPA 350.1)
- Nitrate plus nitrite nitrogen (EPA 353.2)
- Total suspended solids (SM2540D)

Monthly samples from the three larger, named tributary streams were also analyzed for:

- Total recoverable iron (EPA 200.7)
- 5-day biochemical oxygen demand (SM5210B)

A YSI ProDSS multiparameter meter was used for field measurements of temperature, dissolved oxygen, pH, conductivity (specific conductance), and turbidity. The meter was calibrated daily for dissolved oxygen and pH, and monthly for conductivity and turbidity.

Stream Flow Monitoring/Estimation

Stream flow monitoring was conducted by the USGS from May 11th through October 24th for the Pokegama River at Cemetery Road (Figure 7). Flows for missing dates in early May and late October were estimated to be watershed area proportional to USGS flows measured for the Nemadji River at County Highway C. Flows for Bear Creek, Bluff Creek, and bay watershed areas were estimated to be watershed area proportional to flows for the Pokegama River.

Load Estimation

Total phosphorus and 5-day biochemical oxygen demand loads for the Pokegama River were estimated by applying flow regression formulas to estimate daily concentrations and daily loads. Total phosphorus and 5-day biochemical oxygen demand loads for effluent discharge from the Village of Superior wastewater lagoons were estimated using daily discharge flows and weekly sample test results provided by the Village. Sample test results from the nearest tested date were applied to dates not sampled. Additional effluent discharge samples were collected by DNR staff and tested for total phosphorus. DNR collected sample results were similar to Village collected sample results (DNR samples, n=3, mean = 1.7mg/l; Village samples, n=14, mean = 1.7 mg/l).

Bay Water Quality Results and Discussion

Bay Stratification / Profile Data

Temperature

Water temperature data is summarized in Table 7. Coolest near surface ("top") temperatures occurred on May 22nd and ranged from 8.3 to 10.6 °C. Warmest top temperatures occurred on July 10th and 24th and ranged from 21.9 to 26.0 °C. Allouez Bay sites were cooler on most dates from May to September 11th. Seiche-induced inputs of Lake Superior water to the bay probably account for this, since Lake Superior temperatures are cooler than SLRE temperatures during that time period (Oost et al. 2010). Temperatures at the shallow sites, PS and PMID tended to decline readily during periods of cool weather (May 22nd, late September, October) making them similar to Allouez Bay at those times.

Site KND showed the most thermal stratification and had the greatest top to near bottom ("bottom") temperature declines on ten of the twelve monitoring dates (Table 7). Site KND is the second deepest site (5 m, 16.3 ft) and is located at the mouth of Kimballs Bay. Kimballs Bay is fairly narrow, relatively deep, and has steep wooded banks. These characteristics provide protection from wind-induced mixing. Site ASD is the deepest site (5.1 m, 16.6 ft), but shows minimal thermal stratification, probably due to the broad expanse of Allouez Bay allowing frequent wind-induced mixing. Site ANW, a shallower site (2.4 m, 7.9 ft) near the mouth of the bay tended to show more stratification than site ASD. This may be due to seiche-induced inputs of cool Lake Superior water back-flowing along the bottom at times. Such underflows have occasionally been observed at the Superior entrance to Lake Superior (Kiesling 2017).

There was very notable stratification in all three bays on August 29th. Most monitoring sites showed their largest top to bottom temperature declines (-2.0 to -5.8° C) on that date (Table 7). The largest top to bottom conductivity declines (-4 to -77 umhos/cm) occurred at all sites on that date (Table 9). The largest top to bottom turbidity increases (24 to 148 ntu) at all sites except PS (Table 10), and the largest top to bottom dissolved oxygen (D.O.) declines (-2.5 to -4.0 mg/l) at all sites except KND and PS (Table 8) also occurred on that date.

There was a substantial runoff event shortly before August 29th which probably accounts for the stratification that was observed. Peak flow for the runoff event occurred on August 27th. Tributary stream data from three sites was collected on August 28th (Table 11). Stream flows were much cooler and had higher turbidities than near-surface water in the bays. This resulted in stream water being denser and flowing along the bottoms of the bays to produce the observed stratification. Stream parameters measured on August 28th can account for most of the top to bottom differences that are observed in the bays on August 29th.

During peak stream flow (August 27th) it is likely that stream conductivities were even lower, and turbidities were even higher than those measured on August 28th. Dissolved oxygen concentrations may have also been somewhat lower. The stream water entering the bays was layered at the bottom of the bays. Dissolved oxygen concentrations in that stream water were likely to have declined over two days due to biochemical oxygen demand present in the water and sediment oxygen demand.

The tributary to Kimballs Bay was not monitored on August 28th. Other measurements of conductivity in that tributary during moderate flows were as low as 113 umhos/cm, so it is certainly possible that conductivity during a high flow event was less than the 93 umhos/cm measured at the bottom of site KND. Stream conductivities during high flows tend to be lower since recent runoff of rainfall, with a very low conductivity, makes up a larger portion of the flow.

Site KND which had the most prior stratification and bottom D.O. depletion, showed a notable increase in near bottom D.O.'s from August 15th (0.8 mg/l) to August 29th (5.9 mg/l), which also indicates stream runoff water was largely replacing the near bottom water at that sampling site.

Despite the relatively shallow depths at the three Pokegama Bay sites, occasional thermal stratification occurred on dates other than August 29th. Site PMID (depth 1.6 m, 5.4 ft) had the most dates (8 of 12) when top to bottom temperature decline more than 1°C. Even site PS with a depth of only 1 m (3.2 ft) had three dates when top to bottom temperatures declined more than 1°C. Surficial heating from absorption of all solar radiation near the surface of the highly turbid water may account for much of this stratification.

Table 7. Bay Sites Top and Bottom Temperature Data

		TOP TEMPERATURE (TOP TO BOTTOM TEMPERATURE DECLINE) (°C)						
		SITES (Depth (ft))						
Dates		**ASD (16.6)**	**ASE (6.2)**	**ANW (7.9)**	**KND (16.3)**	**PND (10.5)**	**PMID (5.4)**	**PS (3.2)**
5/9/2017		10.6 (0.4)	10.9 (0.7)	10.9 (0.6)	12.4 (1.8)	12.3 (0.2)	13.5 (0.6)	14.5 (0.1)
5/22/2017		8.5 (0.2)	8.8 (0)	8.6 (0)	10.6 (1.5)	9.2 (0.8)	8.4 (0.4)	8.3 (0.1)
6/15/2017		17.2 (1.1)	17.4 (1.3)	17.8 (2.2)	21.6 (3.7)	19.2 (0.4)	20.9 (1.3)	19.7 (0.1)
6/26/2017		17.2 (0.5)	17.3 (0.7)	18.0 (1.3)	19.8 (1.7)	19.2 (0.5)	19.1 (0.6)	18.5 (0)
7/10/2017		21.9 (0.2)	22.6 (0.8)	22.6 (3.2)	24.8 (6.2)	25.7 (2.8)	25.9 (2.5)	23.9 (0.3)
7/24/2017		21.8 (1.1)	21.0 (0.6)	21.3 (1.5)	23.2 (4.0)	23.7 (1.2)	26.0 (3.4)	25.9 (2.7)
8/15/2017		20.5 (0.5)	20.5 (0.7)	21.3 (1.4)	22.1 (3.0)	22.6 (1.2)	22.8 (1.9)	21.7 (0.7)
8/29/2017		19.5 (2.5)	20.3 (3.0)	20.0 (2.0)	21.7 (5.8)	22.1 (5.6)	22.1 (4.8)	20.2 (3.3)
9/11/2017		17.5 (0.2)	17.6 (0.1)	17.7 (0.1)	19.6 (2.6)	19.5 (2.6)	21.8 (3.6)	20.8 (1.1)
9/27/2017		17.0 (0.8)	16.7 (0)	16.5 (0.1)	18.3 (0.8)	18.2 (0.6)	16.8 (1.5)	15.7 (0.2)
10/4/2017		14.8 (0.2)	14.2 (0)	14.7 (0.1)	15.5 (0.4)	14.4 (0.3)	14.4 (0.2)	14.0 (0.1)
10/17/2017		10.6 (0.4)	10.3 (0.1)	10.8 (0.3)	12.5 (1.5)	11.3 (0.5)	11.5 (1.1)	10.2 (0.1)

Top measurements made 0.3 m below water surface; bottom measurements made 0.3 m above bottom.

Table 8. Bay Sites Top and Bottom Dissolved Oxygen Concentration Data

	BOTTOM D.O.'S (D.O. DECLINE FROM TOP TO BOTTOM) MG/L						
	SITE ((DEPTH (FT))						
DATE	ASD (16.6)	ASE (6.2)	ANW (7.9)	KND (16.3)	PND (10.5)	PMID (5.4)	PS (3.2)
5/9/2017	10.2 (0.4)	10.2 (0.7)	10.3 (0.6)	10.6 (0.4)	12.1 (0.2)	12.9 (0.6)	14.4 (0.1)
5/22/2017	10.8 (0.0)	10.6 (0.0)	10.8 (0.1)	9.3 (0.5)	10.0 (0.1)	10.7 (0.0)	10.8 (0.0)
6/15/2017	8.8 (0.6)	8.9 (0.4)	9.4 (0.2)	8.1 (-0.7)	7.3 (0.3)	7.2 (0.2)	4.9 (0.1)
6/26/2017	9.0 (0.0)	9.2 (0.4)	9.1 (0.3)	7.6 (0.2)	7.8 (0.5)	8.5 (0.3)	7.3 (0.0)
7/10/2017	7.5 (0.2)	7.8 (0.9)	8.1 (0.4)	2.2 (5.8)	6.7 (1.8)	6.0 (1.9)	4.0 (0.2)
7/24/2017	6.6 (1.2)	7.2 (0.3)	7.8 (0.4)	0.6 (6.8)	6.1 (0.7)	6.1 (1.5)	3.4 (1.3)
8/15/2017	7.0 (1.6)	8.0 (0.7)	7.7 (1.9)	0.8 (7.8)	5.7 (2.0)	5.6 (1.0)	4.7 (1.5)
8/29/2017	5.5 (4.0)	6.2 (3.8)	6.2 (3.5)	5.9 (2.6)	5.7 (2.5)	6.9 (2.5)	7.2 (-0.2)
9/11/2017	8.2 (0.2)	8.3 (0.1)	8.3 (0.1)	6.3 (1.4)	6.3 (0.7)	5.4 (1.3)	3.7 (0.7)
9/27/2017	7.6 (0.7)	8.3 (0.1)	7.7 (0.2)	7.1 (-0.3)	4.6 (0.7)	6.4 (-0.5)	7.6 (0.0)
10/4/2017	8.2 (0.3)	7.9 (0.1)	8.0 (0.2)	7.3 (-0.5)	7.3 (0.1)	7.7 (0.1)	8.3(0.0)
10/17/2017	10.0 (0.1)	9.9 (0.0)	9.6 (0.2)	8.7 (-0.6)	8.3 (0.3)	6.2 (0.7)	7.8 (0.0)

D.O. = dissolved oxygen. Top measurements made 0.3 m below water surface; bottom measurements made 0.3 m above bottom. Red values are < 5 mg/l.

Table 9. Bay Sites Top and Bottom Conductivity Data

		TOP CONDUCTIVITY (TOP TO BOTTOM CONDUCTIVITY CHANGE)(umhos/cm)						
		SITES (Depth (ft))						
Dates		ASD (16.6)	ASE (6.2)	ANW (7.9)	KND (16.3)	PND (10.5)	PMID (5.4)	PS (3.2)
5/9/2017		138 (0)	138 (0)	135 (3)	112 (-2)	106 (0)	130 (0)	138 (-1)
5/22/2017		126 (-1)	125 (0)	126 (0)	112 (-4)	114 (2)	112 (0)	107 (0)
6/15/2017		136 (-1)	134 (-2)	132 (-4)	124 (+2)	133 (-1)	139 (+2)	173 (0)
6/26/2017		139 (0)	139 (0)	140 (-1)	143 (+6)	152 (+1)	156 (-1)	177 (0)
7/10/2017		147 (0)	146 (0)	147 (-4)	159 (-2)	161 (0)	168 (+1)	190 (-1)
7/24/2017		155 (-6)	151 (+1)	150 (-4)	155 (+7)	157 (0)	171 (+5)	210 (-3)
8/15/2017		158 (+1)	158 (-1)	156 (0)	176 (-11)	182 (0)	187 (+2)	196 (0)
8/29/2017		162 (-21)	164 (-4)	162 (-7)	170 (-77)	172 (-36)	167 (-34)	134 (-7)
9/11/2017		170 (0)	169 (0)	170 (0)	150 (-4)	146 (-6)	151 (+1)	171 (0)
9/27/2017		166 (-2)	167 (0)	164 (+1)	139 (-4)	158 (-6)	158 (-5)	142 (0)
10/4/2017		150 (-7)	113 (0)	110 (-1)	128 (-1)	95 (-2)	94 (0)	109 (0)
10/17/2017		139 (+1)	141 (+1)	141 (0)	120 (0)	116 (-1)	136 (+22)	165 (0)

Top measurements made 0.3 m below water surface; bottom measurements made 0.3 m above bottom. Conductivity is specific conductance.

Table 10. Bay Sites Top and Bottom Turbidity Data

	TOP TURBIDITY (TOP TO BOTTOM TURBIDITY CHANGE) (NTU)						
	SITES (Depth (ft))						
Dates	ASD (16.6)	ASE (6.2)	ANW (7.9)	KND (16.3)	PND (10.5)	PMID (5.4)	PS (3.2)
5/9/2017	91 (10)	83 (12)	85 (10)	13 (1)	25 (2)	135 (-5)	105 (13)
5/22/2017	110 (5)	110 (5)	110 (5)	27 (41)	125 (0)	145 (-5)	117 (0)
6/15/2017	78 (4)	75 (5)	68 (-10)	13 (4)	52 (9)	80 (10)	87 (-2)
6/26/2017	92 (0)	77 (13)	80 (0)	14 (14)	54 (11)	60 (4)	98 (2)
7/10/2017	73 (5)	69 (-2)	77 (-22)	14 (21)	32 (12)	56 (12)	77 (-1)
7/24/2017	54 (24)	55 (2)	55 (6)	13 (20)	36 (6)	40 (7)	45 (2)
8/15/2017	34 (4)	38 (3)	37 (3)	10 (36)	21 (13)	41 (2)	42 (0)
8/29/2017	38 (68)	36 (24)	43 (40)	14 (96)	50 (148)	63 (72)	111 (3)
9/11/2017	48 (0)	47 (0)	49 (1)	15 (10)	52 (0)	59 (7)	56 (0)
9/27/2017	51 (9)	50 (1)	80 (10)	17 (2)	68 (-1)	73 (38)	154 (13)
10/4/2017	80 (30)	195 (-5)	190 (5)	36 (-11)	270 (5)	275 (0)	210 (20)
10/17/2017	76 (4)	70 (10)	73 (1)	29 (-1)	67 (4)	84 (-8)	110 (0)

Top measurements made 0.3 m below water surface; bottom measurements made 0.3 m above bottom.

Table 11. August 27-29th Runoff Event Data for Stream and Bay Sites

Pokegama River Flows		Stream parameters 8/28/2017				
Date	Mean Daily Flow (cfs)	Stream	Temperature (°C)	Dissolved Oxygen (mg/l)	Conductivity (umhos/cm)	Turbidity (ntu)
8/26/2017	18	Pokegama	15.7	9.3	120	139
8/27/2017	325	Bear	16	9.2	123	113
8/28/2017	131	Bluff	15.9	8.8	132	135
8/29/2017	50					
8/30/2017	23					
			Bay parameters 8/29/2017			
		Bay Site	Temperature (°C) (top/bottom)*	Dissolved Oxygen (mg/l) (top/bottom)*	Conductivity (umhos/cm) (top/bottom)*	Turbidity (ntu) (top/bottom)*
		ASD	19.5/17	9.5/5.5	162/141	38/106
		ASE	20.3/17.3	10/6.2	164/160	36/60
		ANW	20/18	9.7/6.2	162/155	43/73
		KND	21.7/15.9	8.5/5.9	170/93	14/110
		PND	22.1/16.5	8.2/5.7	172/136	50/198
		PMID	22.1/17.3	9.4/6.9	167/133	63/135
		PS	20.2/16.9	7.0/7.2	134/127	111/114

*top parameters measured 0.3 m below surface; bottom parameters measured 0.3 m above bottom

Dissolved Oxygen

Thermal stratification can allow isolation of near bottom water which can result in dissolved oxygen depletion and sediment phosphorus release. Dissolved oxygen concentration (D.O.) from site profiles are summarized in Table 8. Site KND, which showed the most summer thermal stratification also showed the most near-bottom D.O. depletion, with near-bottom D.O.'s less than 1 mg/l on two dates. Near-bottom D.O.'s at all sites in Allouez Bay were consistently above 5 mg/l. Near-bottom D.O.'s at sites PND and PS were below 5 mg/l at times.

Since D.O. depletion can result in sediment phosphorus release, additional discussion of D.O. results is contained in the "Sediment P Release Indicators" section, below. The large top to bottom declines in D.O. at most sites on August 29th are believed to be due to tributary stream underflow as discussed above.

Conductivity

Conductivity (specific conductance) from site profiles are summarized in Table 9. All three bays showed similar ranges of top conductivities (Allouez, 110-170; Kimballs, 112-176; Pokegama, 94-210). SLRE main channel conductivities are seasonally variable with May-October 2017monthly means ranging from 117 to 201 umhos/cm (NERR 2017). They are not distinctive from bay c conductivities.

Conductivities showed notable declines from top to bottom at all site on August 29th. These declines are believed to be due to tributary stream underflow as discussed above.

Site ANW at the mouth of Allouez Bay showed fairly consistent top to bottom conductivity and temperature declines between June 15th and August 29th, which suggests more frequent bottom inflow of Lake Superior water into that bay. Lake Superior water conductivity is about 103-104 umhos/cm (Oost et al. 2010, Eliot et al. 2014).
Lake Superior has been shown to be a major water source for Allouez Bay. A mixing assessment done during May through mid-July of 2007 using conservative ions estimated that Lake Superior was the source of 46-50% of Allouez Bay water (Hoffman 2018). The St. Louis River was the source of 50-53% of bay water, and direct tributaries (Bluff Creek) were the source of 1% of bay water. The Nemadji River was not providing any significant amount of water to the bay.

Figure 8. June 2017 Air Photo of Kimballs Bay

Turbidity

Turbidities from site profiles are summarized in Table 10. Kimballs Bay (site KND) had significantly lower top turbidities (mean = 18 ntu) than all other sites. Sites PS and PMID had the highest mean top turbidities (101 ntu, 93 ntu), but mean top turbidities for Pokegama and Allouez Bay sites are not significantly different (Figure 52).

The largest top to bottom turbidity increases at all sites occurred on August 29th. These increases are believed to be due to tributary stream underflow as discussed above.

Site KND showed the most pronounced top to bottom turbidity increases through much of the season. The unnamed tributary to Kimballs Bay, with a mean turbidity of 84 ntu's is the likely source of these increases. Water temperature in the tributary was consistently cooler than bay surface temperature. The cooler, high turbidity inflow probably tends to flow along the bottom in this relatively narrow, deep, and wind sheltered bay. The variable top to bottom conductivity changes at site KND also suggest this flow pattern is occurring. Conductivities in the tributary were also variable (113-289 umhos/cm) and could be higher or lower than top conductivities in the bay. A June 2017 air photo (Figure 8) shows clay turbidity was restricted to the upstream end of Kimballs Bay, which may also indicate that turbid inflow is sinking as at moves downstream through the bay.

Bay Water Chemistry

Phosphorus

Range of Total Phosphorus Concentrations and Seasonal Patterns

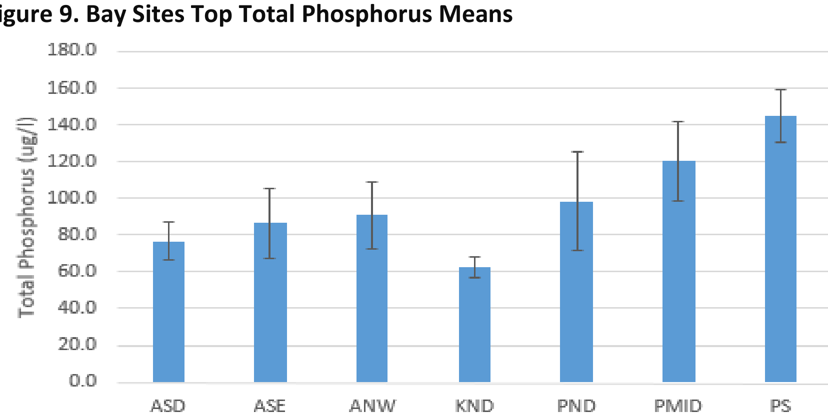
Mean total phosphorus concentrations (TP's) in near surface (top) samples from the bay monitoring sites ranged from 63 ug/l (site KND) to 145 ug/l (site PS) (Figure 9) (Complete bay water quality data is provided in appendix 1). The TP mean for site KND (Kimballs Bay) was significantly lower than the Allouez and Pokegama Bay sites. Sites in Allouez Bay were not significantly different from each other. Site PS in Pokegama Bay was significantly higher than all other sites except site PMD.

The Kimballs Bay site (KND) is close to the mouth of that bay and so is strongly influenced by mixing with estuary water which has lower TP's than the bays. TP inputs from the small unnamed tributary to Kimballs Bay (TP mean = 160 ug/l) are diluted by estuary water, which has lower TP's.

Pokegama Bay mean TP's decreased from the upstream end of the bay (site PS) to the downstream end (site PND). The Pokegama River, which had high TP (mean = 182 ug/l), strongly influenced site PS.

Potential phosphorus release from sediment and fringe wetlands may also have influenced TP at site PS. TP decreases downstream of site PS were probably due to increased mixing with estuary water, which has lower TP's, and sedimentation of particulate phosphorus.

Figure 9. Bay Sites Top Total Phosphorus Means



Error bars are 90% confidence intervals

Some seasonal patterns in near surface (top) TP were evident in Figures 10 - 16, below. All sites, except PS, showed a spring TP peak on May 22nd, and all sites showed a fall TP peak on October 4th. The TP peaks were a result of large runoff events (Figure 17). Sites in Allouez and Pokegama Bay showed lower TP's during mid-summer, generally late July through August, when runoff inputs were low. The Kimballs Bay site showed a different summer pattern, with TP's increasing from mid-June to early September (Figure 13). This was probably due to sediment phosphorus release being more substantial in this bay. Seasonal patterns in near bottom (bottom) TP's are discussed in the "Sediment P Release Indicators" section, below.

Figure 10. Site ASD Top and Bottom Total Phosphorus Concentrations

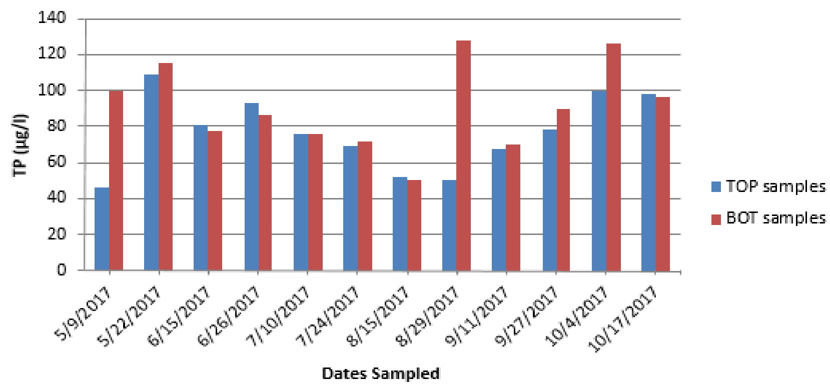


Figure 11. Site ASE Top and Bottom Total Phosphorus Concentrations

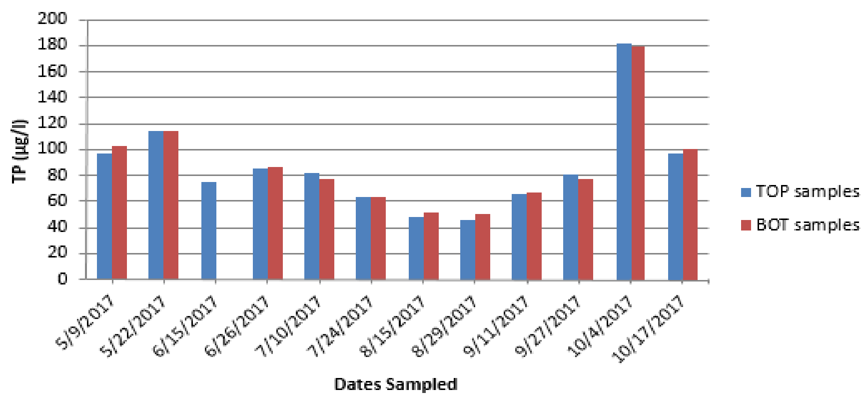


Figure 12. Site ANW Top and Bottom Total Phosphorus Concentrations

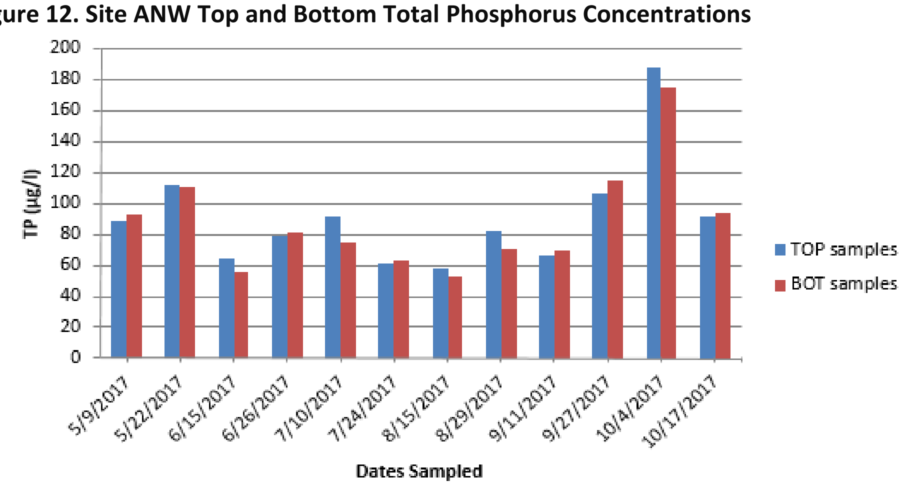


Figure 13. Site KND Top and Bottom Total Phosphorus Concentrations

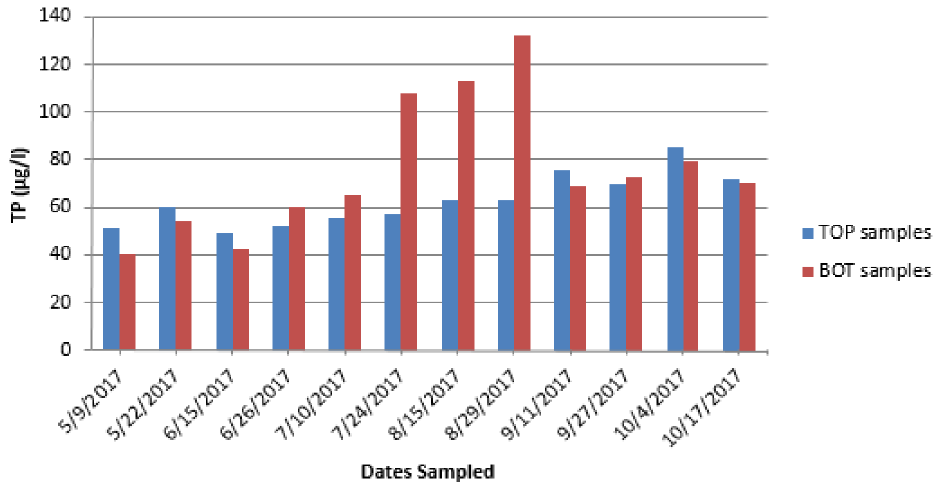


Figure 14. Site PND Top and Bottom Total Phosphorus Concentrations

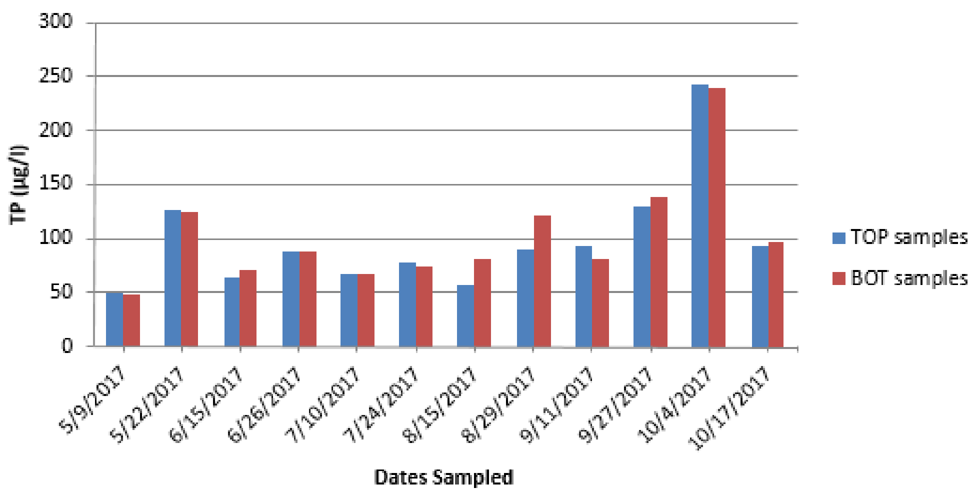


Figure 15. Site PMID Top and Bottom Total Phosphorus Concentrations

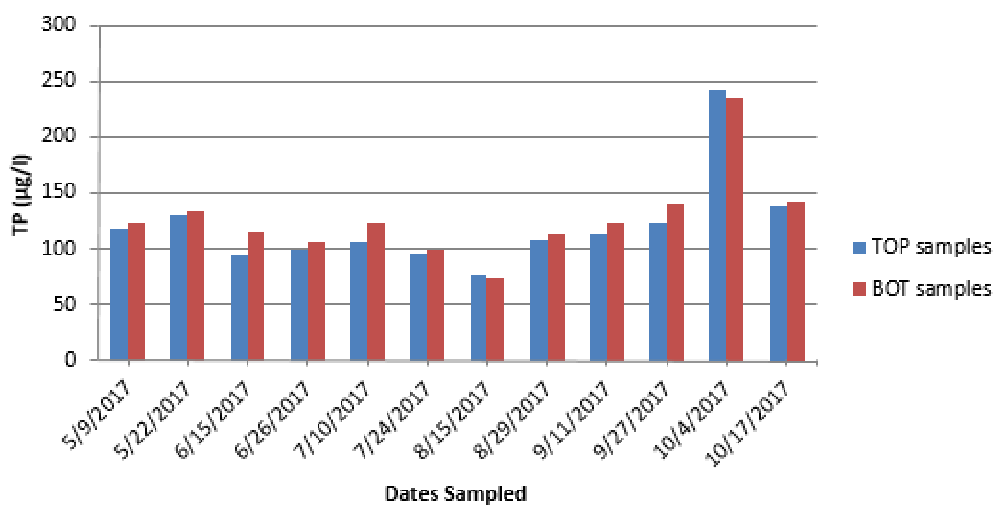


Figure 16. Site PSD Top Total Phosphorus Concentrations

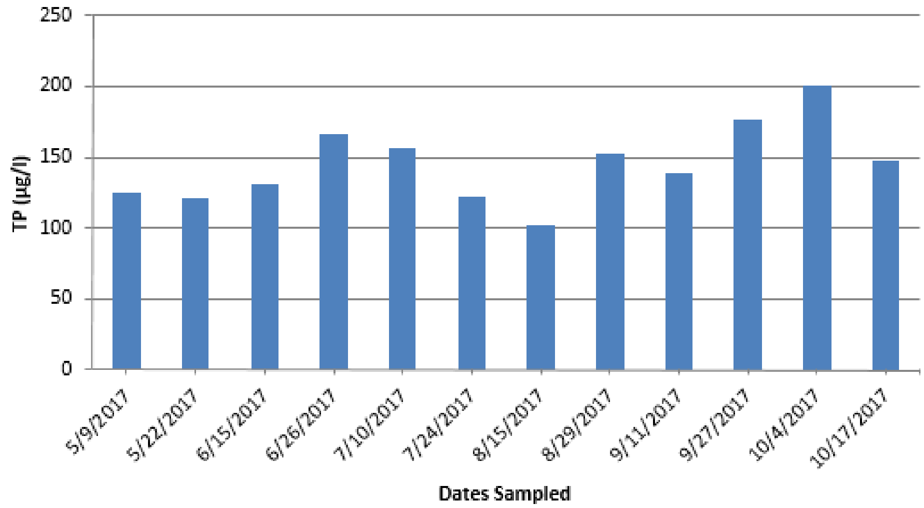
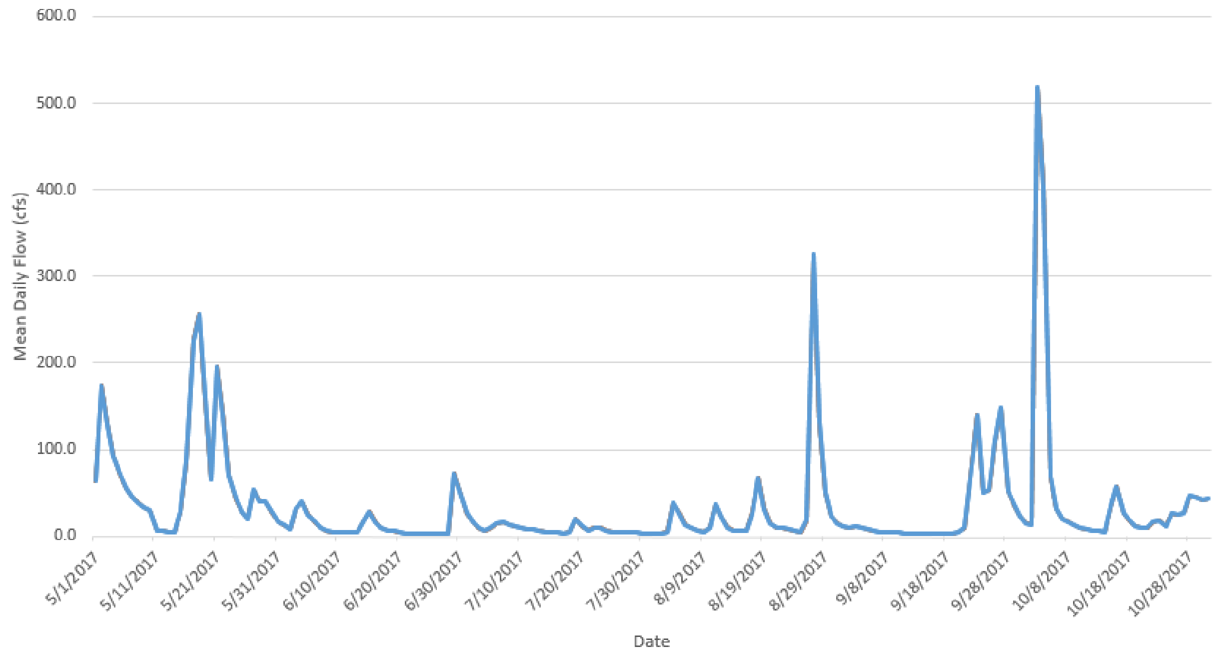


Figure 17. Pokegama River Flows (data from USGS)



Comparison to TP Criteria and Reference TP's

Selecting appropriate TP criteria to apply to these bays is difficult due to their unique hydrologic characteristics. These bays are part of the much larger St. Louis River estuary which is subject to irregular backflows and mixing resulting from Lake Superior seiches.

The WI DNR has a state-wide stream TP impairment threshold of 75 ug/l, and a large river TP impairment threshold of 100 ug/l (applicable to the St. Louis River). However, since these bays are generally not riverine, these thresholds are not suitable for assessing their water quality condition.
The St. Louis River Area of Concern 2016 Remedial Action Plan identifies 30 ug/l goal as the TP target for the St. Louis River estuary (SLRE) (MPCA et al. 2017). This target was selected since it was considered to be the upper limit of the mesotrophic range (or eutrophic threshold). This target is intended to apply to

the open main channel areas of the SLRE and not sheltered bays and was not based on analyses of local data. Mean bay site TP's (63-145 ug/l) are roughly 2-5 times higher than this target concentration. Lake-based TP criteria are probably more suitable for the bays than river-based ones. Lake-based TP criteria include:

- 24 ug/l eutrophic threshold for lakes (Carlson 1977)
- 30 ug/l eutrophic threshold for Wisconsin lakes (Lillie and Mason 1983)
- 40 ug/l Wisconsin impairment threshold for shallow lakes (WIDNR 2017)

These lake thresholds are all substantially lower than TP's found at the bay sites. However, lake TP thresholds are usually developed based on a concern for avoiding undesirable levels of algae production. The relationship between TP and algae production (chlorophyll a concentrations) is substantially different in these bays than in most lakes (see chlorophyll a section below), and so lake thresholds are also not well suited to these bays.

TP's measured at 150 sites throughout the SLRE in 2012 and 2013 (Bellinger et al. 2015) provide another basis of comparison. A mean TP of 31 ug/l was found. Mean TP's for the bay sites (63-145 ug/l) are again roughly 2-5 times higher.

Diatom inferred (DI) TP's for Allouez and Pokegama Bay were determined by Reavie et al. (2016) for both recent and pre-development periods (Table 12). Kimballs Bay was not sampled. Pre-development TP's could be used to help guide the selection of TP targets for these bays. The pre-development DI-TP for Allouez Bay (29.5 ug/l) is close to lake eutrophic threshold values. The pre-development DI-TP for Pokegama Bay (47 ug/l) substantially exceeds lake eutrophic threshold values (Table 12).

2017 median sampled TP's exceed recent DI-TP's for both bays. Recent SLRE TP's (Bellinger et al. 2015) at other core sites were also found to exceed DI-TP's (Reavie et al. 2016). Additionally, one year of bay data may not represent average recent conditions. Also, the DI-TP model may not fully account for the influence of light limitation and the limited bio-availability of the clay-bound TP fraction in the bays.

Table 12. Diatom Inferred Total Phosphorus (DI-TP) for Allouez and Pokegama Bays Compared to 2017 Sampled Total Phosphorus

BAY	PRE-DEVELOPMENT* DI-TP	RECENT** DI-TP	2017 MEDIAN SAMPLED TP	SITE OF 2017 SAMPLING
Allouez	29.5	74	81.3	ASD, ASE, ANW***
Pokegama	47	73	89	PND
	DI-TP values form Reavie, et al. 2016			
	*based on 2 oldest pre-1875 layers			
	*based on 2 most recent post-2000 layers			
	***2017 median is average from 3 sites			

Bay sites were selected that best coincide with the core sampling sites.

Comparison of 2017 TP's and Related Parameters to Data from Other Years

Some TP data along with chlorophyll a (CHL), total suspended solids (TSS), and/or turbidity data is available for other years to compare to 2017 data. Three TP samples collected in 2016 (USGS 2018)

during May, July, and August at site PMID in Pokegama Bay ranged from 85 – 293 ug/l. In 2017, TP's at this site were similar and ranged from 77 – 242 ug/l.
Datasets from 2007 (Hoffman 2011), 2011-12 (Bartsch et al 2015), and 2012-13 (Bellinger et al 2015) for Allouez and Pokegama Bays can also be compared to the 2017 data from these bays (Tables 13, 14, 15). In 2007, TP's and CHL's in Allouez and Pokegama Bays were similar to those found in 2017, but TSS's appear to be significantly higher, with 2007 means over double those found in 2017 (Table 13).

Table 13. Comparison of Total Phosphorus, Chlorophyll a, and Total Suspended Solids Concentrations in Allouez and Pokegama Bays During 2007 and 2017

Bay (site)	Parameter	May-July 2007*(n = 5)	May-July 2017 (n = 6)
Allouez (ASD)	TP (ug/l) mean	85.8	79
Allouez (ASD)	TP (ug/l) range	64 - 155	46 - 109
Allouez (ASD)	CHL (ug/l) mean	10.6	6.9
Allouez (ASD)	CHL (ug/l) range	7.3 - 16.4	3.0 - 14.9
Allouez (ASD)	TSS (mg/l) mean	42.3	19.2
Allouez (ASD)	TSS (mg/l) range	19 - 92	7 - 28
Bay (site)	**Parameter**	**May-July 2007* (n = 15)**	**May-July 2017 (n = 6)**
Pokegama (PND)	TP (ug/l) mean	83.5	78.9
Pokegama (PND)	TP (ug/l) range	36 - 263	49 - 127
Pokegama (PND)	CHL (ug/l) mean	8.8	8.0
Pokegama (PND)	CHL (ug/l) range	1.7 - 21.7	0.5 - 18.7
Pokegama (PND)	TSS (mg/l) mean	39.6	15.6
Pokegama (PND)	TSS (mg/l) range	5.2 - 269	7.7 - 37
*Hoffman 2011			

TP = total phosphorus; CHL = chlorophyll a; TSS = total suspended solids

Data from 2010-11 (Bartsch et al 2015) (Table 14) was from three site composite samples from sites near tributary mouths, while 2017 data is from mid-bay sites further from tributary mouths. Because of this, the 2010-11 data might be expected to have higher TP's and turbidities, and possibly lower CHL's. However, there were no significant differences in any of the parameter means at the 90% confidence level.

Table 14. Comparison of Total Phosphorus and Chlorophyll a Concentrations, and Turbidities in Allouez and Pokegama Bays During 2010-11 and 2017

Months and Years of Samples	Bay; No. sites; No. samples	TP (ug/l) mean (+/-90% C.I.)	TP (ug/l) range	CHL (ug/l) mean (+/- 90% C.I.)	CHL (ug/l) range	TURB (ntu) mean (+/- 90% C.I.)	TURB (ntu) range
September 2010, May and August 2011*	Allouez; 3 sites; n = 7	94 (+/- 25.1)	68 - 126	6.5 (+/- 5.1)	0.6 - 24	67 (+/-16.2)	36 - 95
May, August, and September 2017	Allouez; 3 sites; n = 18	76 (+/- 9.3)	46 - 115	8.8 (+/- 3.4)	2.1 - 26.6	62 (+/- 13.6)	28 - 123
September 2010, May and August 2011*	Pokegama; 2 sites; n = 6	108 (+/- 20.5)	68 - 142	5.7 (+/- 3.2)	2.6 - 15.1	54.6 (+/-25.7)	19 - 121
May, August, and September 2017	Pokegama; 2 sites; n = 12	101 (+/- 13.4)	49 - 130	6.5 (+/- 3.1)	0.5 - 23.4	70 (+/- 21.8)	17 - 155
*2010 and 2011 data from Bartsch et al 2015. Three site composite samples from sites near tributary mouths were tested.							
TP = total phosphorus; CHL = chlorophyll a; TURB = turbidity							

Data from 2012-13 (Bellinger et al 2015) (Table 15) showed no significant differences from 2017 data for CHL, TSS, and turbidity in Allouez and Pokegama Bays at the 90% confidence level. However, there was a very significant difference in TP for both bays, with 2012-13 values being much lower than 2017 values.

Table 15. Comparison of Total Phosphorus, Chlorophyll a, and Total Suspended Solids Concentrations, and Turbidities in Allouez and Pokegama Bays During 2012-13 and 2017

	ALLOUEZ BAY		POKEGAMA BAY			ALLOUEZ BAY		POKEGAMA BAY	
	May, Jul, Aug, Sep 2012; May, Jun, Jul, Aug, Sep, Nov 2013	May-Oct 2017	Aug, Sep 2012; June, Aug 2013	June, Aug, Sep 2017		May, Jul, Aug, Sep 2012; May, Jun, Jul, Aug, Sep, Nov 2013	May-Oct 2017	Aug, Sep 2012; June, Aug 2013	June, Aug, Sep 2017
Chl a (µg L-1)					**TSS(mg L-1)**				
mean	10.9	7.1	13.0	7.5	mean	29.8	20.9	23.2	11.6
median	8.5	4.7	11.0	4.7	median	24.7	15.0	19.3	12.2
range	2.6 - 32	1.0 - 26.6	4.6 - 21.1	2.0 - 23.4	range	9.0 - 62.7	5 - 122	7.0 - 36.7	5.4 - 17.5
n	32	18	7	12	n	32	18	7	12
S.D.	6.8	6.2	6.6	6.1	S.D.	16.9	23.3	11.7	4.7
90% CI	2.0	2.4	4.1	2.9	90% CI	4.9	9.0	7.3	2.2
lower 90% CL	8.9	4.7	8.9	4.6	lower 90% CL	24.9	11.9	15.9	9.3
upper 90% CL	12.9	9.5	17.1	10.4	upper 90% CL	34.7	29.9	30.4	13.8
TP (µg L-1)					**Turbidity (ntu)**				
mean	32.2	84.6	37.1	94.7	mean	81.9	71.4	52.9	50.4
median	27.0	75.4	31.7	93.0	median	63.3	65.1	55.5	49.0
range	20.5 - 59.2	45.5 - 188	16.9 - 64.7	57.6 - 130	range	24.1 - 184	27.5 - 206	13.1 - 105	16.8 - 73.2
n	29	18	6	12	n	32	18	7	12
S.D.	11.5	31.2	16.6	22.1	S.D.	51.6	40.9	31.4	16.6
90% CI	3.5	12.1	11.1	10.5	90% CI	15.0	15.9	19.5	7.9
lower 90% CL	28.7	72.5	25.9	84.2	lower 90% CL	66.9	55.6	33.4	42.6
upper 90% CL	35.7	96.7	48.2	105	upper 90% CL	96.9	87.3	72.4	58.3

For Allouez and Pokegama Bays 2017 TP's were similar to those found in 2007 and 2011-12, but not 2012-13. 2017 TSS's were similar to those found in 2011-12 and 2012-13, but not 2007. The poor correlation between TP and TSS (Figure 49, $R^2 = 0.22$) may help explain the variation in the annual relationships for these two parameters. 2017 CHL's were similar to all three of the other data sets. 2017 turbidities were similar to the two other years with data (2011-12, 2012-13). In general, 2017 water quality conditions were fairly typical of what has been found previously, but the bays have the potential for substantial year to year variability. There was insufficient data for Kimballs Bay in the data sets above to provide meaningful comparisons between years.

Bay wetland site water quality data from July or August 2011-2017 is also compared to 2017 bay water quality data in the "Wetland Water Quality Data" section. Mean concentrations for the wetland water quality parameters were generally within the range of open water values found at nearby sites in the respective bays in July and August of 2017 (Table 36). One exception was Kimballs Bay where the wetland mean TP was about double that found at the open water site. The TP difference suggests wetland phosphorus release is occurring in Kimballs Bay.

Sediment Phosphorus Release

Sediment phosphorus (P) release can be a significant P source under some circumstances. Sediment P release can occur under aerobic conditions during periods of high pH (Anderson 1975). pH values > 8.5-9 are typically required for significant phosphorus release (James 2018). Maximum near surface pH's at the bay sites were 8.1 – 8.3 during July and August (appendix 1). pH's declined to ≤ 8 at a depth of 1 meter, and maximum near bottom pH's were 7.9. pH values are probably too low to make pH-induced sediment P release significant in the open water areas of the three bays.

Sediment P release can also occur if anoxia develops at the sediment surface. Iron bound phosphorus is then released to the water column as orthophosphate (Wetzel 2001). Some of the orthophosphate can be adsorbed by suspended particulates, taken up by bacteria, or re-bound to iron complexes that precipitate as oxygen is re-encountered. An examination of increases in near bottom TP's and orthophosphate concentrations (OP's) along with thermal stratification and decreases in near bottom dissolved oxygen concentrations (D.O.'s) can provide evidence of sediment P release.

Sediment P Release Indicators

Seasonal patterns of top and bottom TP's and OP's provided evidence of sediment P release at some sites. Site KND showed top to bottom TP and DOP increases from July 10th to August 29th (Figures 13 and 22). Those dates had the lowest bottom D.O.'s and the greatest top to bottom temperature decreases for the season. A substantial fraction of bottom TP was OP (25 – 43%) on these four dates. Top to bottom ammonia nitrogen concentrations also increased substantially on these dates (Figure 40), which is also consistent with very low D.O. in bottom water. The two dates with the lowest bottom D.O.'s (July 24th, 0.6 mg/l and August 15th, 0.8 mg/l) had the highest top to bottom OP increases. All these observations indicate sediment P release was substantial and prolonged at this site. On August 29th, Site KND was also influenced by the underflow of stream water entering the bay during a runoff event just prior to that date. Much of the top to bottom differences on that date were due to this (see discussion of August 29th bay profiles in the Bay Stratification / Profile Data section).

Site ASD showed top to bottom TP and OP increases on August 29th (Figures 10 and 19). This probably, again resulted from the underflow of stream water entering the bay just prior to that date (see discussion of August 29th bay profiles in the Bay Stratification / Profile Data section). TP's and OP's measured in Bear and Bluff Creeks on August 28th were higher than those found at the bottom of site ASD on August 29th, and so can account for the observed top to bottom increases observed. Sediment phosphorus release is not indicated.

Site PND showed indications of occasional sediment phosphorus release. Top to bottom DOP increased 5.6 ug/l, and top to bottom TP increased 23.2 ug/l on August 15th (Figures 14 and 23). OP comprised 24% of the top to bottom TP increase. Bottom D.O. on August 15th was moderately low at 5.7 mg/l. Site PS near the upstream end of Pokegama Bay is too shallow (1 m, 3.2 ft) to allow top and bottom TP and OP sampling. However, summer daytime D.O.'s were frequently < 5 mg/l (Table 8). On one date, September 11th, a top D.O. of 2 mg/l was found near the edge of the adjacent wetland, while the top D.O. at site PS was 4.4 mg/l. Pokegama Bay is narrow at this site and bordered by wetlands. There is probably potential for sediment or wetland P release in the vicinity of site PS.

The monitoring design used for this project had limited ability to fully assess the extent of D.O. depletion, sediment phosphorus release, and potential wetland phosphorus release. All site D.O. measurements were made during late morning to early afternoon in open water areas. Diurnal fluctuations in D.O.'s probably result in lower D.O.'s occurring at night. D.O.'s adjacent to, and in wetlands are likely to be lower than at open water sites.

The influence of wetlands adjacent to the bays may be substantial. Decomposition of organic matter in wetlands can result in relatively rapid D.O. depletion and subsequent release of iron bound phosphorus from sediment. Seiche-induced pulses of water into and out of these wetlands may enhance the phosphorus cycling process.

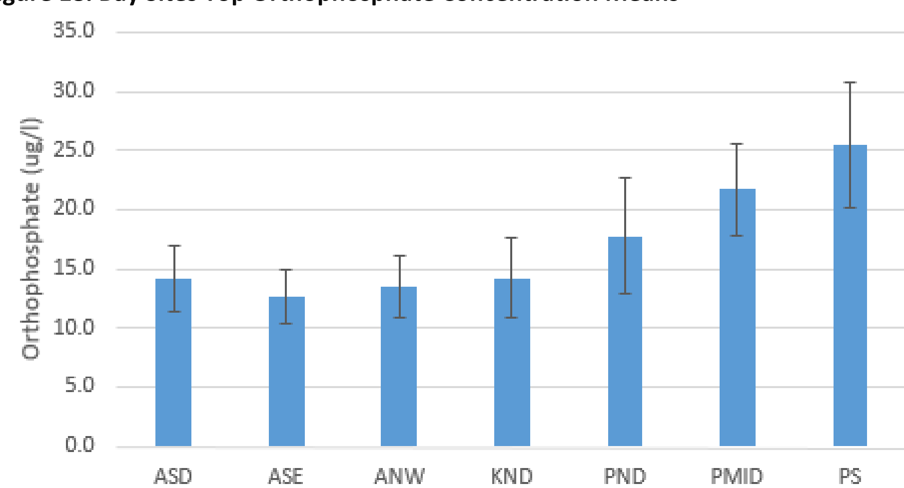
Orthophosphate (Top)

Orthophosphate is the phosphorus form immediately available for algal uptake. Orthophosphate is also the phosphorus form released from anoxic sediment. The relationship between top to bottom TP increases and top to bottom orthophosphate concentration (OP) increases at bay sites is discussed in the preceding section.

Mean OP's in top samples ranged from 12.7 ug/l (site ASE) to 25.5 ug/l (site PS) (Figure 18). The three sites in Pokegama Bay had the highest mean OP's. Sites PS and PMID had significantly higher mean OP's than the Allouez and Kimballs Bay sites. This may be partially due to release of OP from the wetlands that fringe the upstream end of Pokegama Bay and the downstream end of the Pokegama River. The timing of discharges of wastewater lagoon effluent from the Village of Superior to the Pokegama River (primarily May and October) did not appear to be correlated with higher OP's in Pokegama Bay (Figures 23-25), and so are unlikely to be a major source of the elevated OP's in the Bay. However, lagoon effluent phosphorus delivered to the bay will contribute to the pool of phosphorus available for release at other times of the year. Lower OP's in Allouez Bay were probably influenced by inputs of Lake Superior water with low OP's.

Suspended red clay in the SLRE area has been shown to adsorb orthophosphate when high OP's occur (Bahnick 1980). Orthophosphate adsorption by clay occurs when an equilibrium concentration of 20 - 42 ug/l is exceeded. Mean bay site OP's (12.7 – 25.5 ug/l) are within or below this concentration range, suggesting suspended clay may be contributing to the maintenance of lower OP's.

Figure 18. Bay Sites Top Orthophosphate Concentration Means



Error bars are 90% confidence intervals

The percent of mean top TP as OP ranged from 15% (ASE) to 23 % (KND) (Table 16). Allouez Bay tended to have lower percentages partly due to low OP's. Kimballs Bay (KND) had the highest percentage partly due to low TP.

Table 16. Bay Sites % of Total Phosphorus as Orthophosphate

Bay Site	ASD	ASE	ANW	KND	PND	PMID	PS
Mean top TP (ug/l)	76.7	86.4	90.8	62.8	98.2	120.5	144.8
Mean top OP (ug/l)	14.1	12.7	13.5	14.3	17.7	21.7	25.5
% TP as OP	18.4	14.7	14.9	22.7	18.0	18.1	17.6

Top OP's were lowest at most sites on August 15th and August 29th (Figures 19 - 25). High chlorophyll a concentrations occurred at that time (Figure 27) and algal uptake converts OP to TP. Tributary stream OP's were also relatively low at that time (Figure 68). Top Bay OP's tended to be highest at most sites during late September and October. The Pokegama Bay sites were more variable. Release of orthophosphate from decomposition of algae and aquatic macrophytes and reduced orthophosphate uptake by declining algae populations (Figure 27) may account for the higher fall OP's at most sites.

Figure 19. Site ASD Top and Bottom Orthophosphate Concentrations

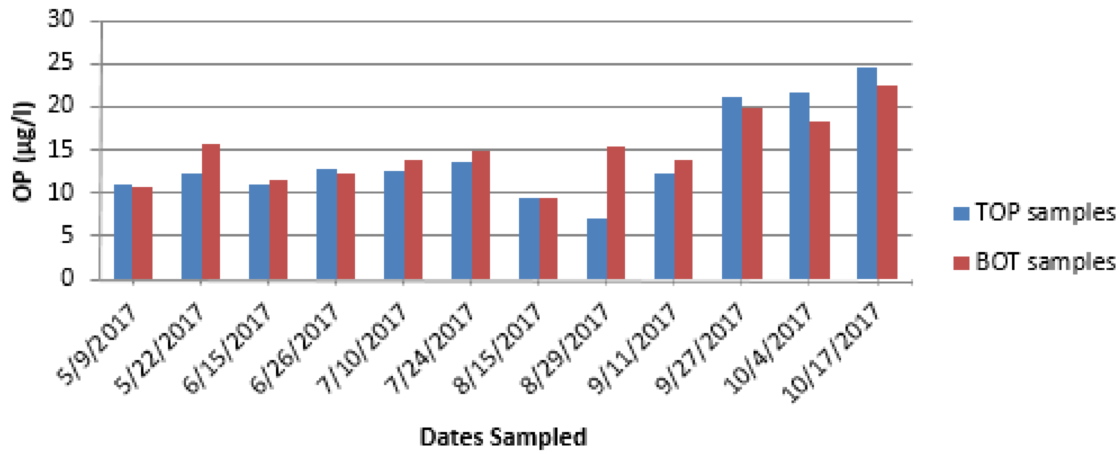


Figure 20. Site ASE Top and Bottom Orthophosphate Concentrations

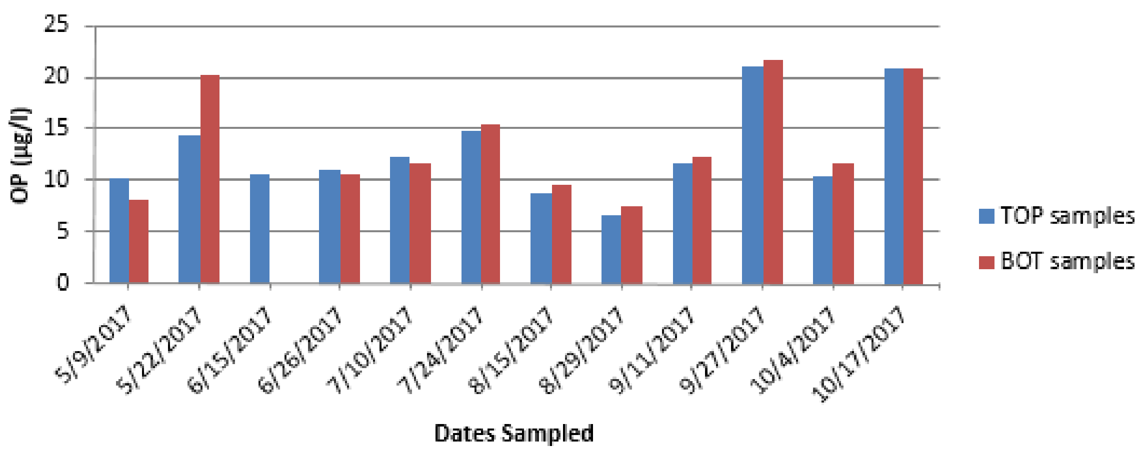


Figure 21. Site ANW Top and Bottom Orthophosphate Concentrations

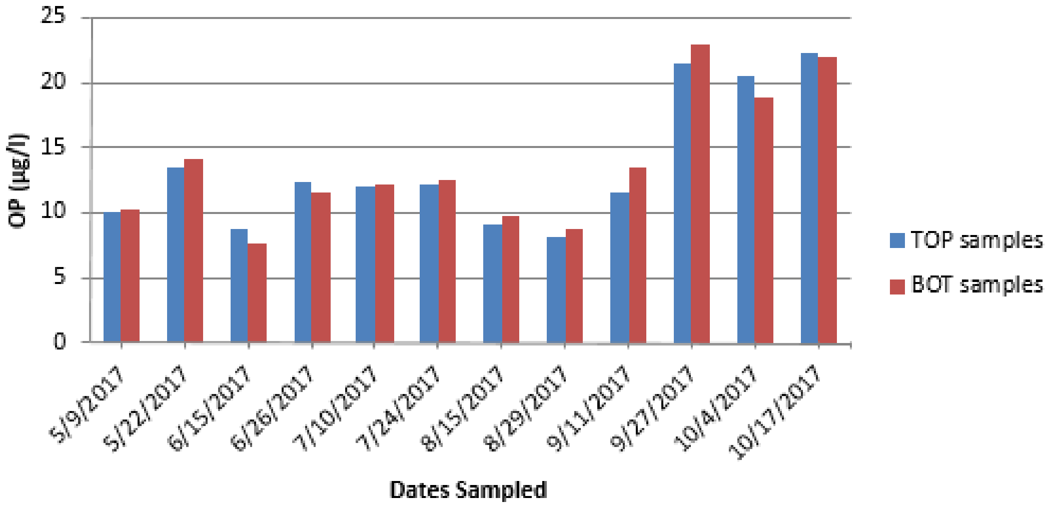


Figure 22. Site KND Top and Bottom Orthophosphate Concentrations

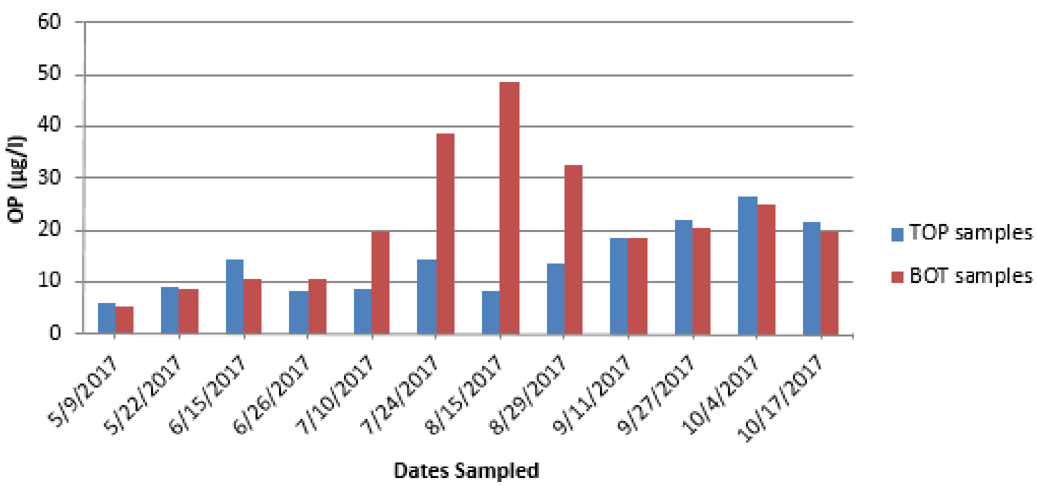


Figure 23. Site PND Top and Bottom Orthophosphate Concentrations

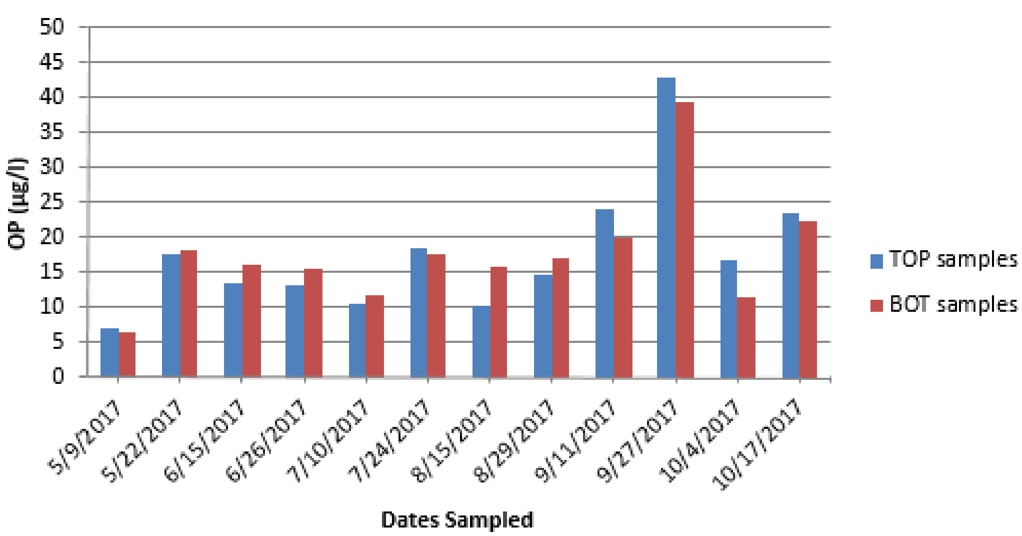


Figure 24. Site PMID Top and Bottom Orthophosphate Concentrations

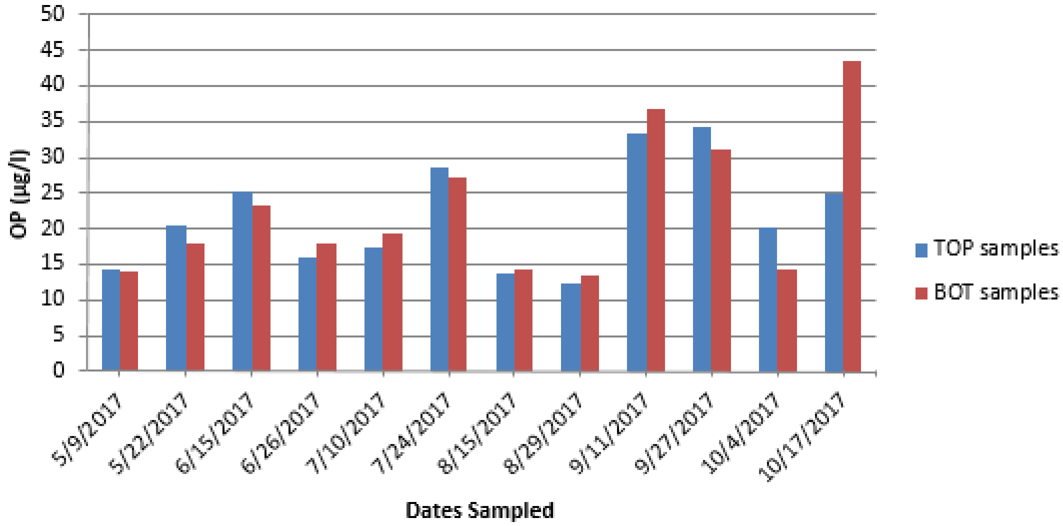
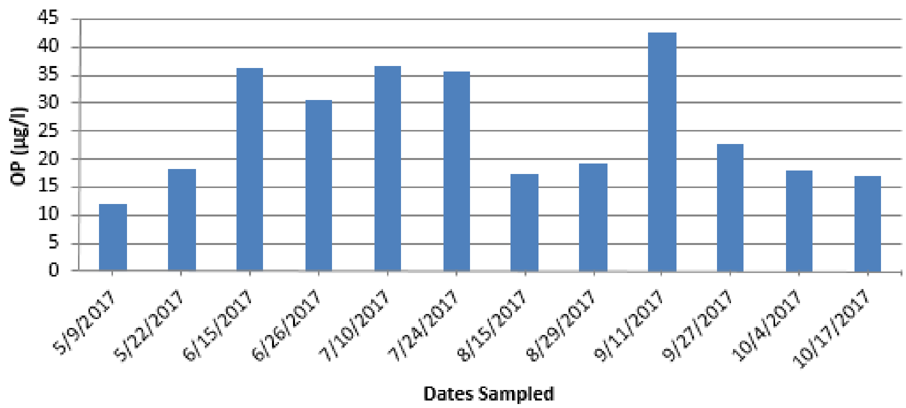


Figure 25. Site PS Top Orthophosphate Concentrations

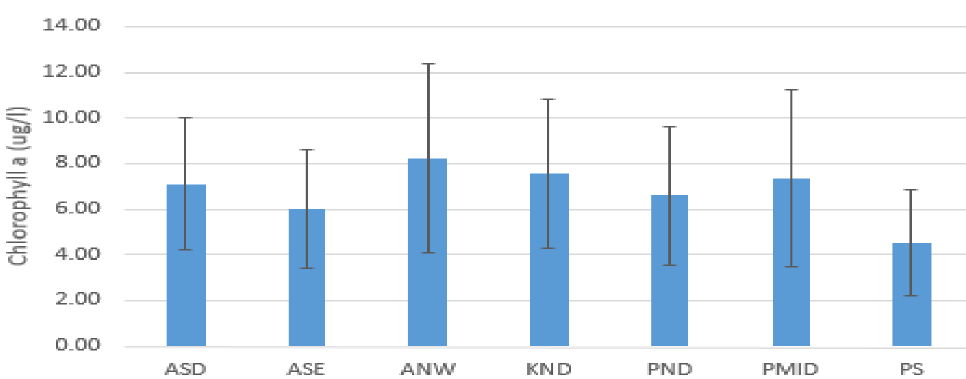


Chlorophyll a

Range and Seasonal Patterns of Chlorophyll a Concentrations

Mean chlorophyll a concentrations (CHL's) ranged from 4.5 ug/l (site PS) to 8.2 ug/l (site ANW) (Figure 26). Site PS at the upstream end of Pokegama Bay had the lowest mean CHL, but differences between sites were not significant.

Figure 26. Bay Sites Chlorophyll a Concentration Means



Error bars are 90% confidence intervals

Highest CHL's tended to occur in July and August (Figure 27). Three July and August samples exceeded 20 ug/l, with the highest CHL at 26.6 ug/l in Allouez Bay at site ANW. Turbidity and total suspended solids concentrations were low during these months (Figures 47 and 53), so potential light limitation of algae growth was reduced. Warmer water temperatures in those months may have contributed to algal growth, especially blue-green algae growth. Total algal cell densities were also highest in July and August (Figure 81).

Allouez Bay also had moderately high CHL's on May 9th (7-11 ug/l) and June 15th (11-15 ug/l) (Figures 27 and 28). Allouez Bay also had higher algal cell densities than the other two bays in May and June (Figure 81).

Figure 27. Allouez, Kimballs, and Pokegama Bays Chlorophyll a Concentrations

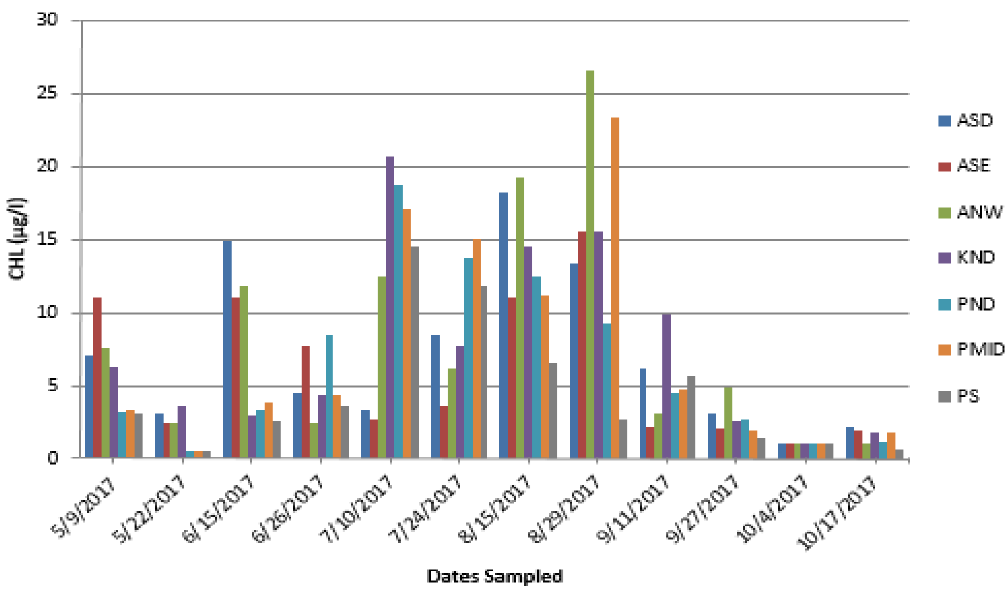


Figure 28. Allouez Bay Chlorophyll a Concentrations

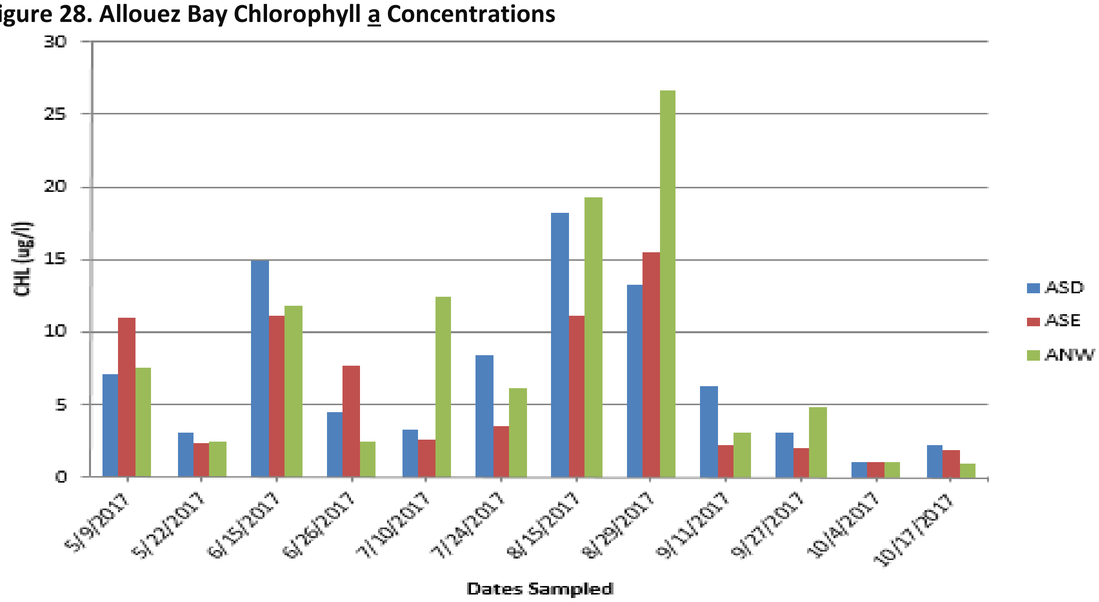
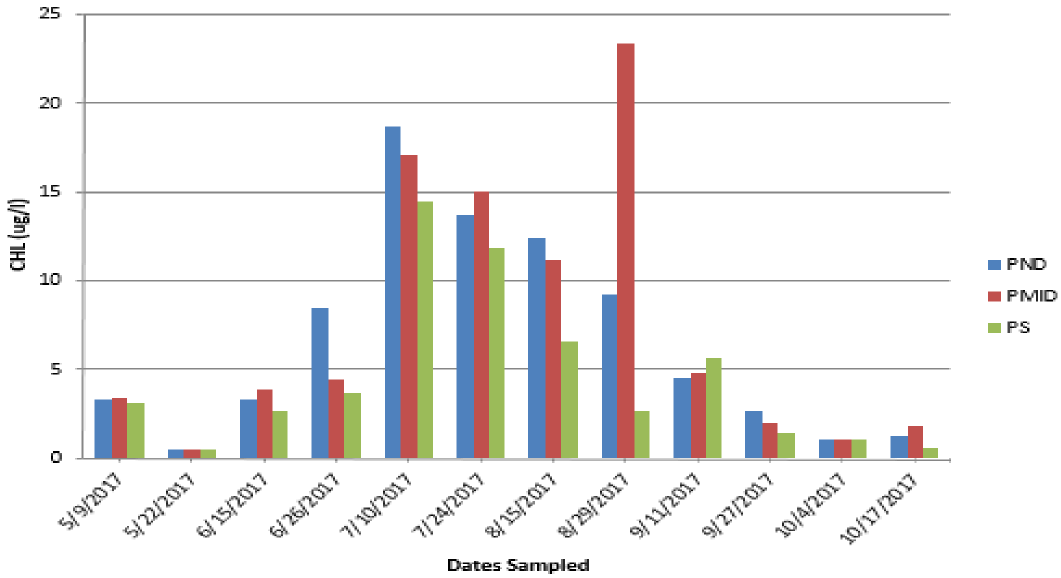


Figure 29. Pokegama Bay Chlorophyll a Concentrations



Comparison to CHL Criteria and Reference CHL's

The St. Louis River Area of Concern 2016 Remedial Action Plan identified 10 ug/l goal as the CHL target for the St. Louis River estuary (SLRE) (MPCA et al. 2017). This target was intended to apply to the open main channel areas of the SLRE but not sheltered bays. Mean CHL's at the bay sites were below this goal.

CHL's were measured at 150 sites throughout the SLRE in 2012 and 2013 (Bellinger et al. 2015). Median CHL's of 6.0 ug/l and 6.3 ug/l were found for 2012 and 2013 respectively. These medians are higher than those found at sites in the three bays (2.9 – 5.5 ug/l), despite the much higher TP's in the bays. This also suggests limitation of algal growth by factors other than TP in the bays.

A CHL of 10.7 ug/l was identified as a threshold for eutrophic lakes in Wisconsin by Lillie and Mason (1983). A CHL of 20 ug/l is considered to indicate a nuisance algal bloom (WI DNR 2017). The Wisconsin Dept. of Natural Resources (WI DNR) (2017) has a recreational impairment threshold for CHL in shallow lakes based on >30% of days having CHL's exceeding 20 ug/l during July 15th through September 15th. The upper 90% confidence limit of the mean number of days must be $\leq$ 30% for a lake to "clearly meet" this criterion. The combined sites from Pokegama Bay clearly met this criterion (mean = 9%; upper 90% C.I. = 25%). The combined sites from Allouez Bay "may meet" this criterion (mean = 15%; upper 90% C.I. = 33%). The site in Kimballs Bay also may meet this criterion (mean = 7%; upper 90% C.I. = 40%). Additional monitoring might lower these 90% C.I.'s below 30%. All bay mean values are well below 30%. The WI DNR also has a fish and aquatic life impairment threshold for CHL in shallow lakes of 27 ug/l (based on the upper bound of the 90% confidence interval of the mean CHL). CHL's from all bay sites fell below this threshold.

Bay CHL's in 2017 were similar to CHL's measured in 2007, 2010-11, and 2012-13 (Tables 13, 14, 15).

CHL relationship to other Trophic State Indices

Trophic state indices (TSI's) are often used to categorize lake nutrient and productivity levels. TP's, CHL's, and Secchi depth (a measure of water clarity) have been used to develop TSI's (Carlson 1977), since these parameters typically provide inter-related measures of lake nutrient and productivity levels. TSI's for bay site median TP's, CHL's and Secchi depths (SD's) are shown in Table 17. If these parameters have a typical relationship, their TSI values will be similar. These relationships were largely derived from water bodies where algal biomass (i.e. chlorophyll) was limited by TP and where water clarity (i.e. Secchi depth) was regulated by algal particulate material.

Bay site TSI values were very different for the three parameters (Table 17) indicating an atypical relationship. For the TP's present, much higher CHL's would normally be expected. CHL's were only a small fraction, 2.9 – 18.5%, of expected concentrations. SD's were also lower than would normally be expected. SD TSI's were much higher than TP TSI's.

Table 17. Bay Sites Trophic State Index (TSI) Values

SLRE BAYS TSI* VALUES								
					TP TSI	MEDIAN CHL		
	MEDIAN	TP	MEDIAN	CHL	"NORMAL"	AS % OF	MEDIAN	SECCHI
SITE	TP (UG/L)	TSI	CHL (UG/L)	TSI	CHL (UG/L)	"NORMAL" CHL	SECCHI (M)	TSI
ASD	77.3	67	5.4	47	40.2	13.4	0.23	81
ASE	81.3	68	3	41	43.3	6.9	0.24	81
ANW	85.4	68	5.5	47	46.6	11.8	0.21	82
KND	61.4	64	5.3	47	28.7	18.5	0.73	65
PND	89	69	3.9	44	49.5	7.9	0.30	77
PMID	111	72	4.2	45	68.5	6.1	0.23	81
PS	143	76	2.9	41	99.4	2.9	0.21	82

TSI relationships from Carlson (1977).

The poor water clarity due to suspended clay and silt, rather than algal cells, is the probable reason for these altered relationships. High turbidities due to suspended inorganic particles have been shown to cause light limitation of algal growth in other water bodies (Wetzel 2001). Also, a portion of the TP in the three bays is bound to suspended clay particles and is less bio-available, as has been observed in the SLRE area (Bahnick 1980) and elsewhere (DePinto et al. 1981). Short residence times might also limit full algal response to available phosphorus at some sites, especially site PS. The poor water clarity (low SD's) is controlled more by suspended inorganic particles than suspended algae. This greatly limits the use of TSI's for these bays.

Lack of typical lake-derived TSI parameter relationships complicates water quality goal setting. It makes it difficult to predict responses to water quality improvements.

Nitrogen

Mean nitrogen parameter values for the bay sites are shown in Figures 30 – 32, 35, 36, and 44. Median nitrogen parameter values for the bay sites are shown in Table 18.

Table 18. Bay Sites Median Values for Nitrogen Parameters

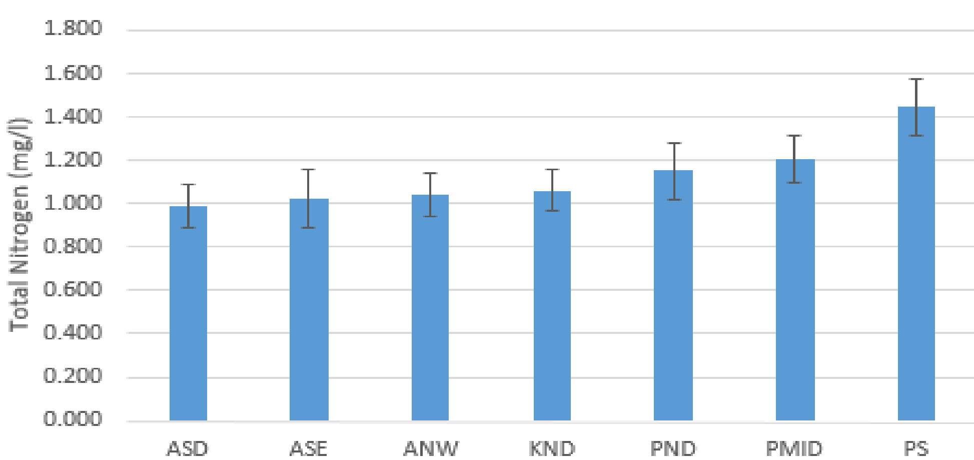
	SITES						
	ASD	ASE	ANW	KND	PND	PMID	PS
NH_3-N top (ug/l)	39.5	41.3	34.8	43.8	35.9	39.9	49
NH_3-N bottom (ug/l)	42.6	39.5	42.7	57.8	53.5	44.2	no data
$NO_3 + NO_2$-N (ug/l)	125	116	126	34.8	51.8	34.5	9.5
TKN (ug/l)	924	880	913	977	1030	1090	1420
Organic N (ug/l)	885	839	878	933	989	1050	1370
% TKN as organic N	96	95	96	96	96	96	96
Dissolved TKN (ug/l)	667	608	637	764	895	820	929
% TKN dissolved	72	69	70	78	87	75	66
Dissolved organic N (ug/l)	627	567	602	720	859	780	880
Particulate organic N (ug/l)	258	272	276	213	130	268	486
Total dissolved N (ug/l)	792	724	763	798	947	855	939
Total Nitrogen (ug/l)	1050	1000	1040	1010	1080	1120	1420
Diss. org. N / Part. org. N	2.4	2.1	2.2	3.4	6.6	2.9	1.8

NH_3-N = ammonia; NO_3+NO_2-N = nitrate plus nitrite; TKN = total Kjeldahl nitrogen; organic N, dissolved organic N, particulate organic N, total dissolved N, and total N concentrations were determined by calculations using lab-measured parameters; Top samples collected 0.5 m below water surface; Bottom samples collected 0.5 m above sediment surface.

Total Nitrogen, Total Kjeldahl Nitrogen and Organic Nitrogen

Mean total nitrogen concentrations (TN's) ranged from 0.989 mg/l (site ASD) to 1.44 mg/l (site PS) (Figure 30). The mean TN at site PS was significantly higher than at all other sites. This was probably due to the strong influence of the Pokegama River which had a mean TN of 1.57 mg/l. The mean TP at site PMID was significantly higher than at site ASD, the site with the lowest mean TP. This, again, was mostly due to Pokegama River influence on site PMID. Samples collected in 2012 and 2013 throughout the SLRE had slightly lower median TN's (2012 – 0.963 mg/l, 2013 – 0.905 mg/l) (Bellinger 2015) than the bay sites (1.00 – 1.42 mg/l).

Figure 30. Bay Sites Total Nitrogen Concentration Means



Error bars are 90% confidence intervals

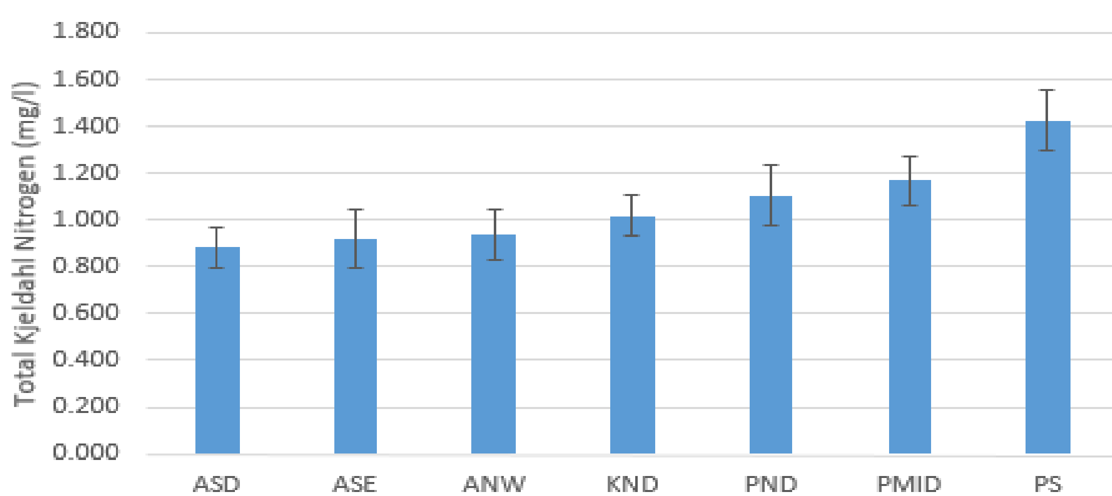
Mean total Kjeldahl nitrogen concentrations (TKN's) ranged from 0.881 mg/l (site ASD) to 1.43 mg/l (site PS) (Figure 31). The mean TKN for site PS was significantly higher than all other sites. The mean TKN for site PMID was significantly higher than the three Allouez Bay sites. Pokegama River influence probably accounted for the higher TKN values at the two Pokegama Bay sites. The Pokegama River had a mean TKN of 1.51 mg/l.

Mean dissolved total Kjeldahl nitrogen concentrations (DTKN's) ranged from 0.649 mg/l (site ANW) to 0.974 mg/l (site PS) (Figure 32). All Pokegama Bay sites had significantly higher mean DTKN's than Allouez Bay sites. The mean DTKN for site PS was significantly higher than for site KND. Pokegama Bay sites were probably, again, influenced by Pokegama River inputs. Dilution with Lake Superior water may have accounted for the lower mean DTKN's in Allouez Bay.

Seasonal TKN patterns were minimal (Figure 33). In Allouez Bay, lowest TKN's occurred in mid-summer, and highest TKN's occurred in October. In Kimballs and Pokegama Bay there were no notable mid-summer TKN declines. Higher TKN's for most sites occurred in late September and October. Release of dissolved organic nitrogen from decomposing vegetation may contribute to this. Stream TKN's also tended to be somewhat higher at that time. Seasonal DTKN patterns generally appear similar to TKN patterns (Figure 34).

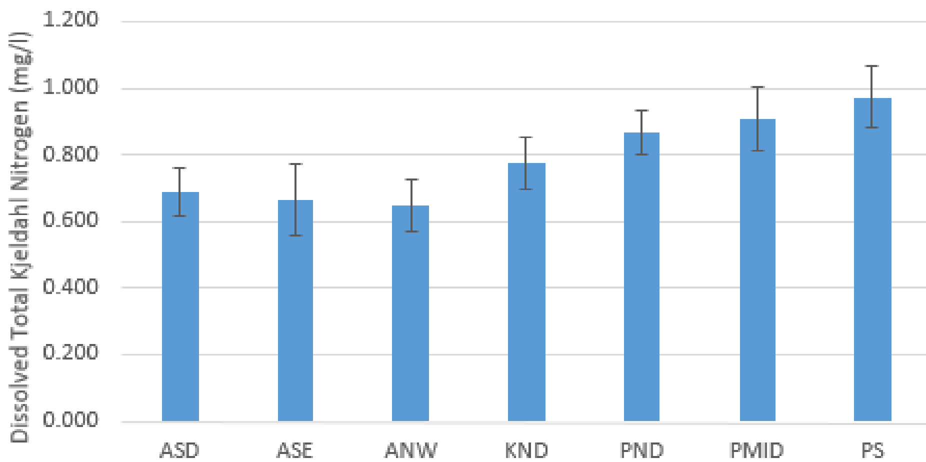
Greater than 95% of TKN was present as organic nitrogen at all sites (Table 18). Most TKN was in a dissolved form (65.7 – 87.3 %). Dissolved TKN is comprised of dissolved organic nitrogen and ammonia. Much of dissolved organic nitrogen is in forms resistant to bacterial degradation, while some forms can be readily utilized by bacteria (Chan and Campbell 1978).

Figure 31. Bay Sites Total Kjeldahl Nitrogen Concentration Means



Error bars are 90% confidence intervals

Figure 32. Bay Sites Dissolved Total Kjeldahl Nitrogen Concentration Means



Error bars are 90% confidence intervals

Figure 33. Bay Sites Total Kjeldahl Nitrogen Concentrations

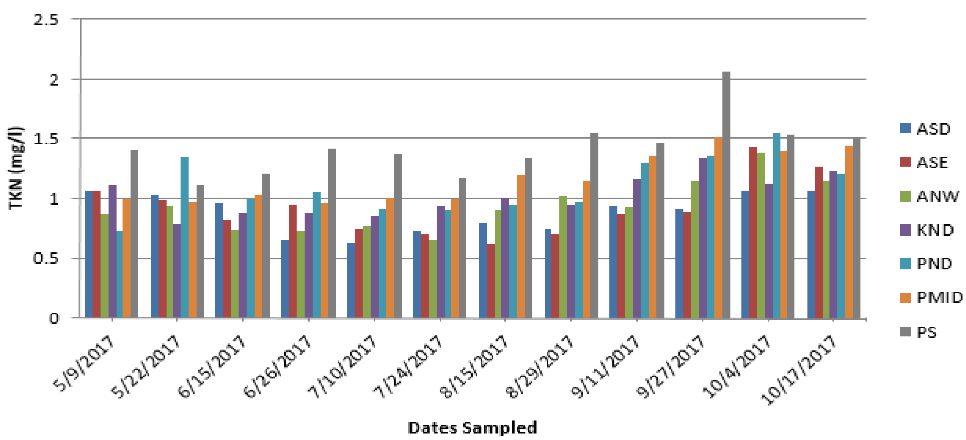
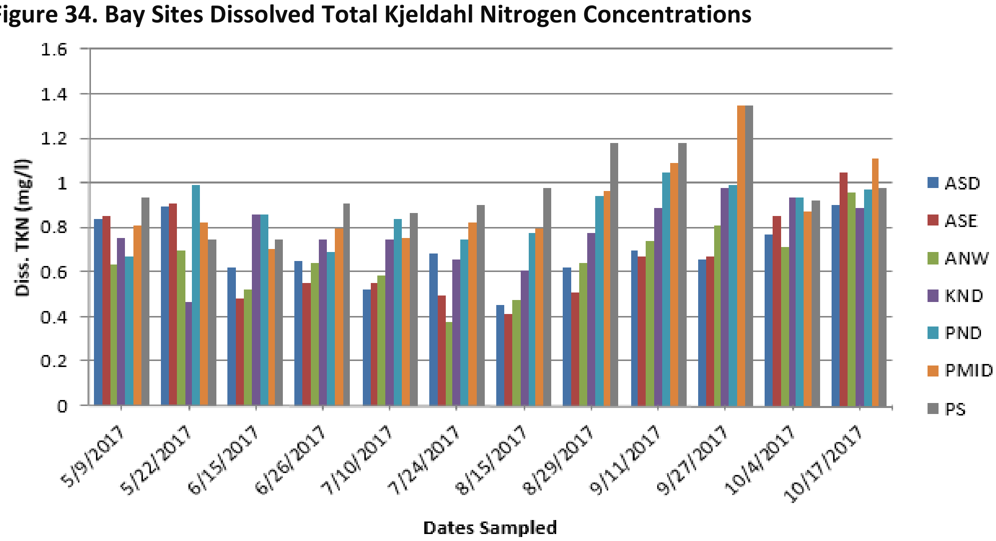


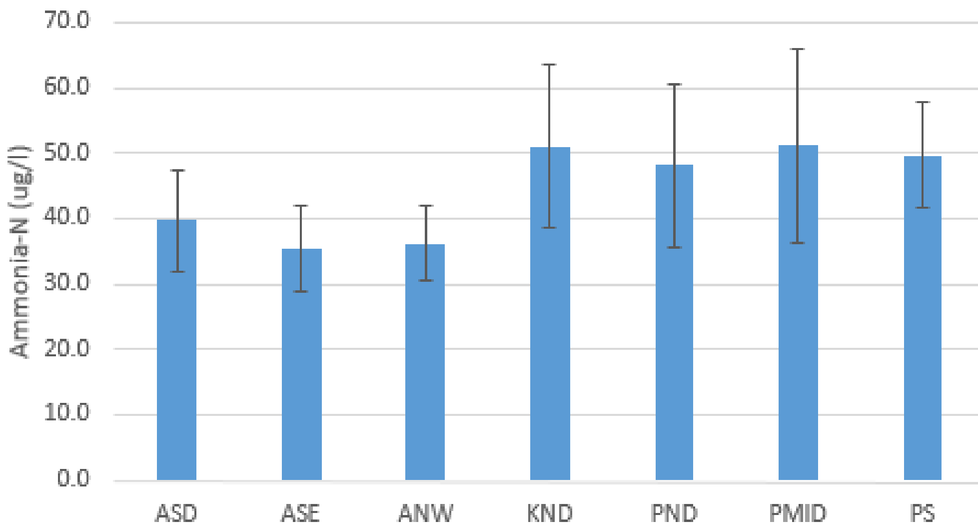
Figure 34. Bay Sites Dissolved Total Kjeldahl Nitrogen Concentrations



Ammonia Nitrogen

Mean top ammonia nitrogen concentrations (NH_3's) were not significantly different across sites and range from 35.4 ug/l (site ASE) to 51.2 ug/l (site PMID) (Figure 35). The pooled top NH_3's from Allouez Bay sites were significantly lower than the pooled top NH_3's from the Pokegama Bay sites. This was probably due to dilution with Lake Superior water in Allouez Bay and the influence of Pokegama River water on Pokegama Bay. Samples collected in 2012 and 2013 throughout the SLRE had median NH_3's (2012 – 29.5 ug/l, 2013 – 26.6 ug/l) (Bellinger 2015) that were lower than bay site medians (34.8 – 49.0 ug/l) (Table 18). Higher NH_3's in the bays were probably due to greater influence of organic matter decomposition in wetlands and in shallow water sediments. Additionally, bay tributary streams had higher median NH_3's (41-46 ug/l) than the SLRE.

Figure 35. Bay Site Top Ammonia-N Concentration Means

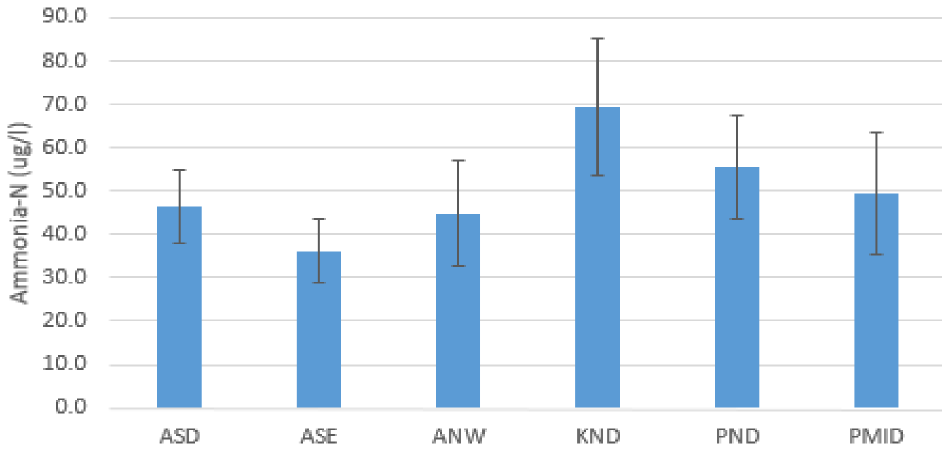


Error bars are 90% confidence intervals

Mean bottom NH_3's ranged from 36.2 ug/l (site ASE) to 69.3 ug/l (site KND). The mean bottom NH_3 was significantly higher at site KND than at site ASE. Site KND had the most extensive bottom oxygen depletion, which can contribute to increased NH_3's by reducing bacterial nitrification of ammonia to nitrate. Increased mineralization of ammonia from sediments rich in organic nitrogen will also lead to higher levels of NH3 in bottom waters. The three Allouez Bay sites had mean bottom NH_3's that were lower than the means for Kimballs and Pokegama Bay. This may again be due to dilution with Lake Superior water in Allouez Bay.

In Allouez Bay, NH_3 tended to be lower in early May and July through August (Figures 37, 38, 39). Uptake of NH_3 by algae probably accounted for this. CHL's in Allouez Bay were high during those periods (Figure 28). A spike in NH_3 in the bottom sample at site ASD on August 29th was probably influenced by the underflow of stream water entering the bay just prior to that date (see discussion of August 29th bay profiles in the Bay Stratification / Profile Data section).

Figure 36. Bay Site Bottom Ammonia-N Concentration Means



Error bars are 90% confidence intervals

At the Kimballs Bay site (KND), NH_3 in top samples tended to be lower in May and late June through August (Figure 40). This was again, likely due to algal uptake of NH_3, since CHL's also tended to be highest during those periods (Figure 27). Bottom sample NH_3's were highest during July and August, probably due to a combination of oxygen depletion and high rates of organic matter decomposition.

In Pokegama Bay, NH_3 patterns were more variable, with somewhat of a tendency to be lower in May and summer (Figures 41, 42, 43). Summer CHL's were also higher in the bay (Figure 29). NH_3's were higher at sites PND and PMID on August 15th, possibly due to a period of dissolved oxygen depletion, also suggested by elevated dissolved orthophosphate in the bottom sample at site PND on that date (Figure 23).

Figure 37. Site ASD Top and Bottom Ammonia-N Concentrations

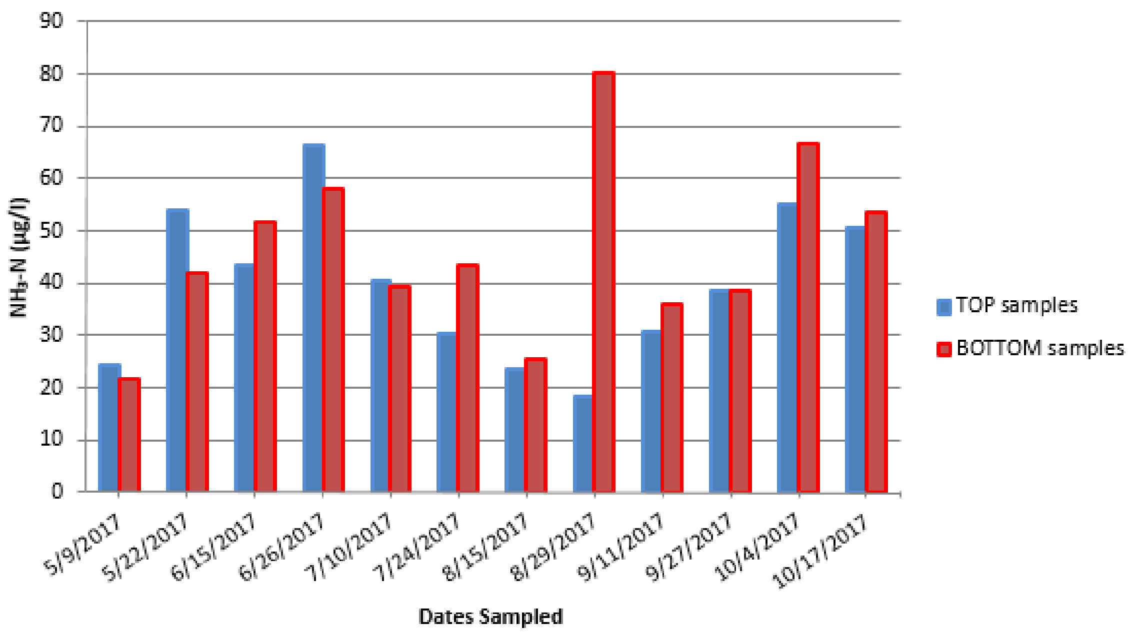


Figure 38. Site ASE Top and Bottom Ammonia-N Concentrations

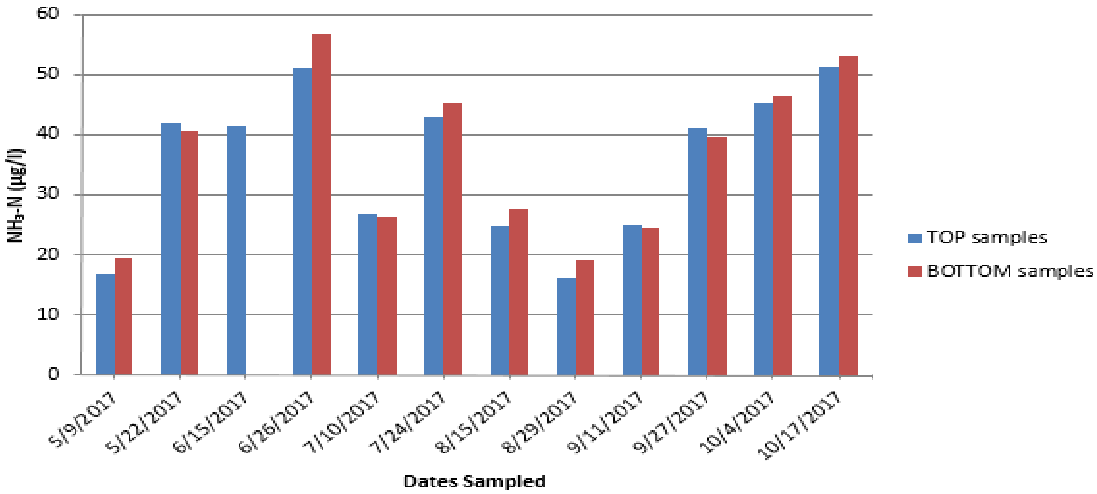


Figure 39. Site ANW Top and Bottom Ammonia-N Concentrations

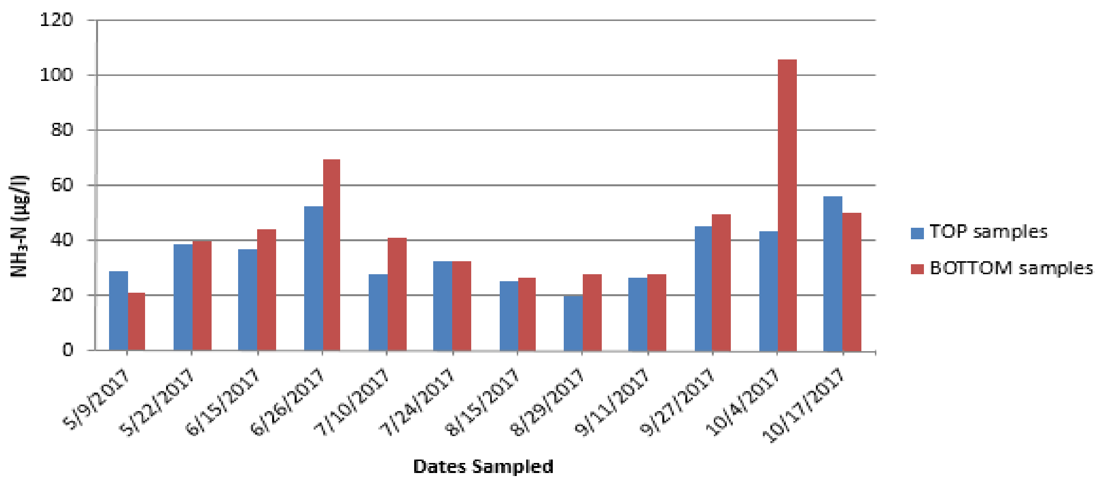


Figure 40. Site KND Top and Bottom Ammonia-N Concentrations

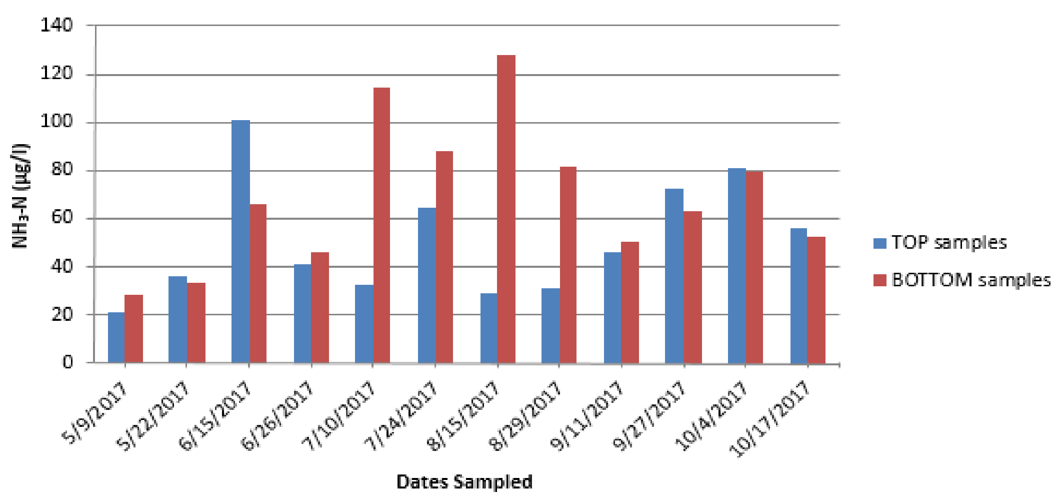


Figure 41. Site PND Top and Bottom Ammonia-N Concentrations

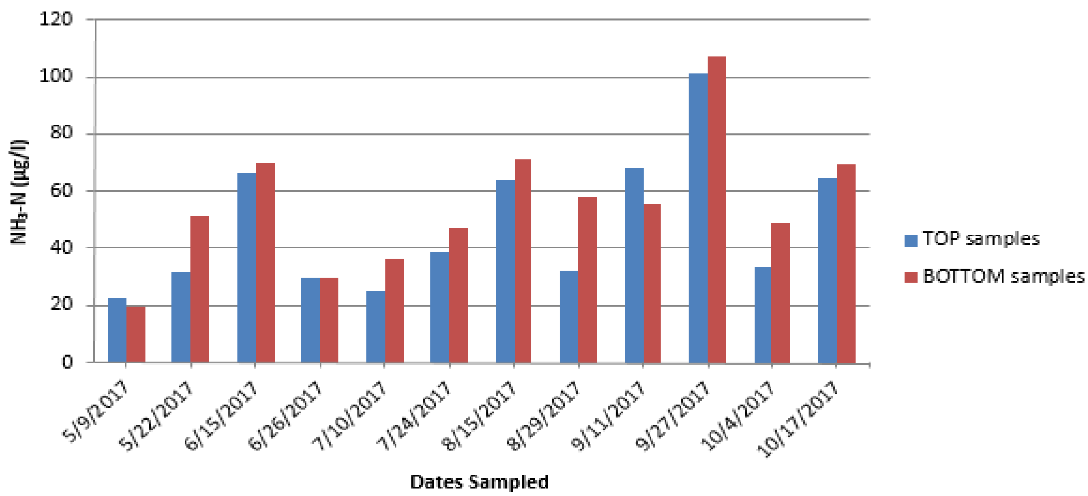


Figure 42. Site PMID Top and Bottom Ammonia-N Concentrations

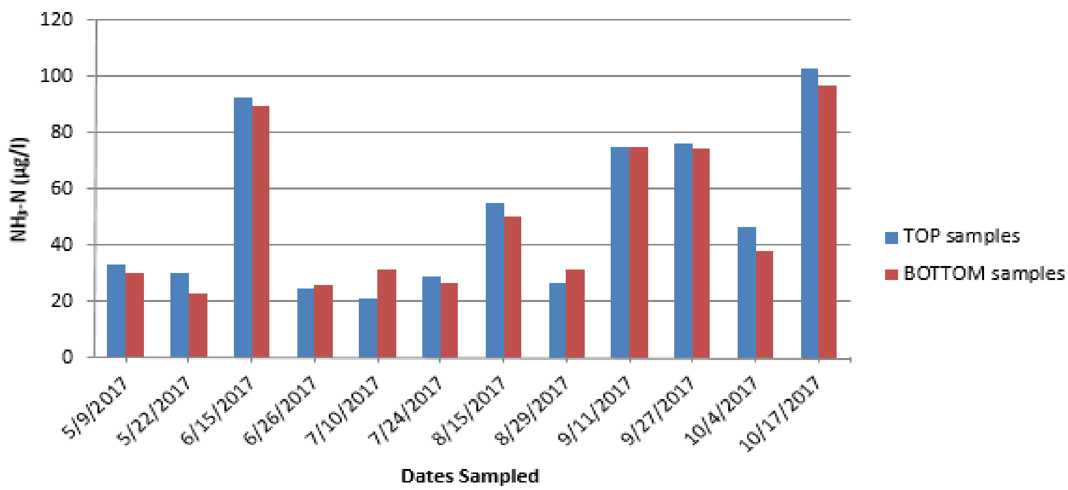
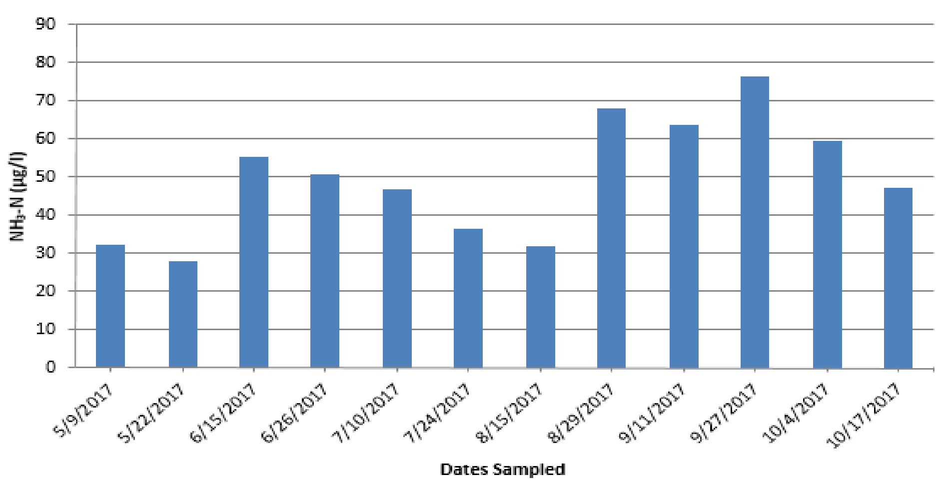


Figure 43. Site PS Top Ammonia-N Concentrations

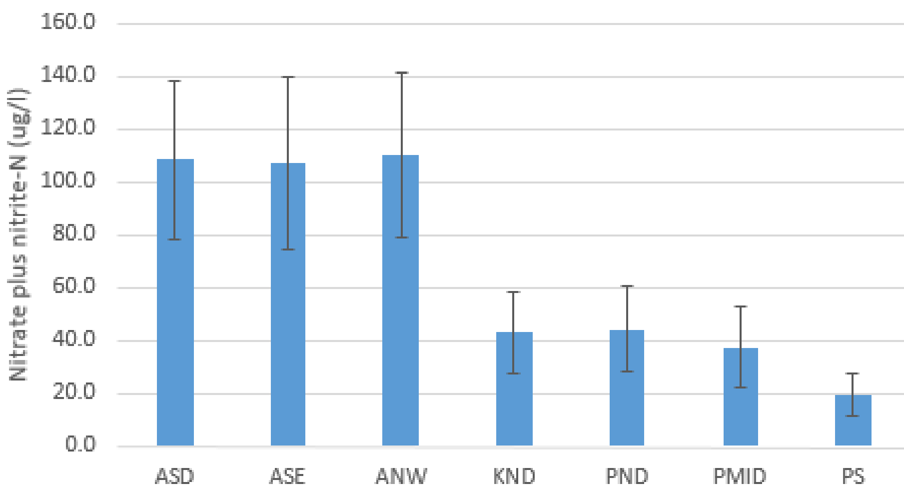


Nitrate plus Nitrite Nitrogen

Mean nitrate plus nitrite nitrogen concentrations (NOx's) ranged from 19.4 ug/l (site PS) to 110 ug/l (site ANW) (Figure 44). The mean NOx for site PS was significantly lower than site PND and the three Allouez Bay sites. Mean NOx's for the three Allouez Bay sites were significantly higher than all other sites. Site PS had the lowest mean NOx, probably due to greater rates of denitrification in this wetland influenced area, with periodic dissolved oxygen depletion. The Allouez Bay sites had the highest mean NOx's (106.9 – 110.4 ug/l), probably due to inputs of water from Lake Superior. The mean May – October 2013 NOx in the near-shore waters of Lake Superior was 321.5 ug/l (Bellinger 2015).

Samples collected in 2012 and 2013 throughout the SLRE had higher median NOx's (2012 – 135.4 ug/l, 2013 – 153.4 ug/l) (Bellinger 2015) than the bay sites (9.5 -126 ug/l). Inputs of Lake Superior water also raise median NOx values in the SLRE, while denitrification due to wetland influence and dissolved oxygen depletion lower median NOx values in the bays.

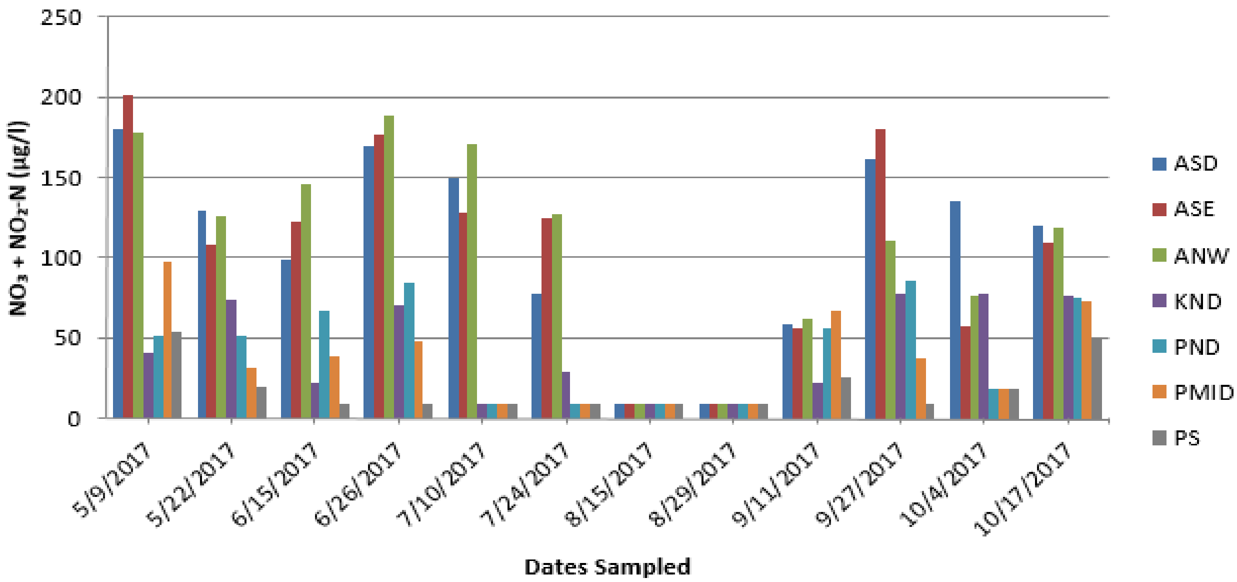
Figure 44. Bay Sites Nitrate plus Nitrite-N Concentration Means



Error bars are 90% confidence intervals

NOx's were generally lowest in the summer (Figure 45). NOx's in Kimballs and Pokegama Bays were almost entirely below detection levels in July and August. NOx's in Allouez Bay were also below detection levels in August. Uptake of nitrate by algae probably accounts for this pattern. Chlorophyll a concentrations peaked during July and August (Figure 27).

Figure 45. Bay Sites Nitrate plus Nitrite-N Concentrations



Nitrogen to Phosphorus Ratios

Nitrogen to phosphorus (N:P) ratios can, in some cases, provide an indication of whether nitrogen or phosphorus is likely to be the limiting nutrient for algal growth. A guide for evaluating Wisconsin lake N:P ratios indicates N:P ratios >15 indicate phosphorus limitation, N:P ratios < 10 indicate nitrogen limitation, and N:P ratios of 10 -15 are transitional (Shaw, et al. 1993).

Summarized total nitrogen to total phosphorus (N:P) ratios for the seven bay sites are shown in Table 19. Most median N:P ratios at the bay sites were in the transitional range (10-15). Site KND's (Kimbals Bay) median N:P ratio slightly exceeded 15, suggesting phosphorus limitation, while site PS's (Pokegama Bay, south) median N:P ratio was slightly less than 10, suggesting nitrogen limitation. Site KND probably receives the greatest contributions from estuary water. Site PS is the most riverine site and is strongly influenced by Pokegama River water inputs. N:P ratios for the primary tributary streams to Allouez and Pokegama Bays are shown in Table 20. Median N:P ratios for the stream sites (8.3 – 10.4) were lower than most bay site ratios, except for site PS

Nutrient limitations suggested by N:P ratios for the bays may be of limited value. TP is only partially bioavailable due to bonding to suspended clay particles (Bahnick 1980, DePinto et al. 1981). The potential for light limitation of algal growth also complicates the use of N:P ratios.

Table 19. N:P Ratios for Bay Sites

	SITE						
	ASD	ASE	ANW	KND	PND	PMID	PS
MEAN:	13.7	12.5	12.2	17.1	13.0	10.6	10.1
MEDIAN:	12.6	13.0	12.2	16.6	13.2	10.6	9.9
MIN:	8.9	8.2	7.7	14.0	6.5	5.8	7.7
MAX:	27.0	15.7	15.7	22.6	16.9	15.6	13.1

Table 20. N:P Ratios for Bay Tributaries

	STREAM		
	Bear Ck.	Bluff Ck.	Pokegama R.
MEAN:	9.6	8.1	9.8
MEDIAN:	10.4	8.3	10.3
MIN:	5.2	2.5	4.4
MAX:	13.8	11.9	16.2

Suspended Solids and Turbidity

Median suspended solids and turbidity values are shown in Table 21. Mean suspended solids and turbidity values are shown in Figures 46, 50, and 52. Mean total suspended solids concentrations (TSS's) ranged from 5.2 mg/l (site KND) to 42 mg/l (site PS). The mean total suspended solids concentration for Site KND was significantly lower than all other sites except PND and ASE. Site KND was strongly influenced by mixing with SLRE water.

Table 21. Bay Sites Suspended Solids and Turbidity Parameter Medians

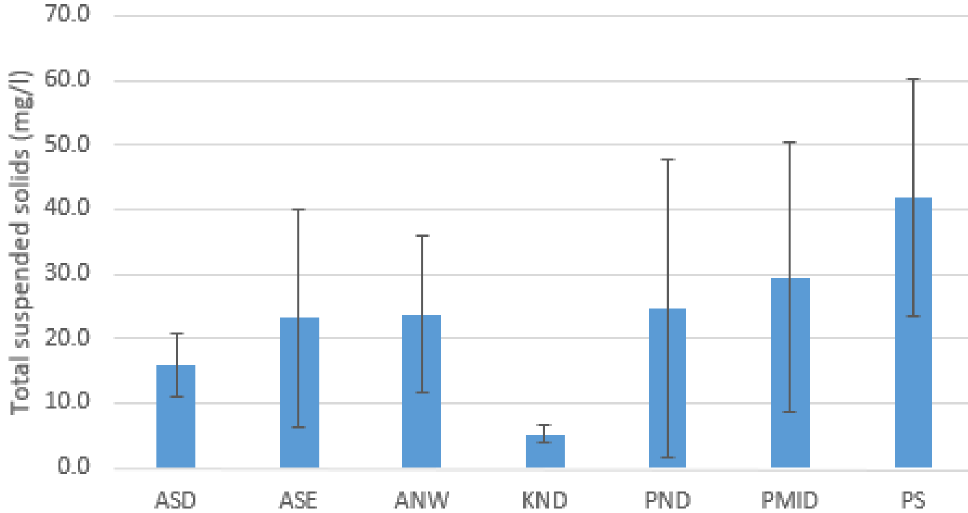
	SITES						
	ASD	ASE	ANW	KND	PND	PMID	PS
TSS (mg/l)	11.6	15	17.0	4.3	10	15	33.3
Volatile TSS (mg/l)	2.5	2.5	1.9	1.6	2	2.7	4.7
% TSS volatile	21.5	16.3	11.4	36.0	20.0	18.0	14.0
Turbidity (ntu)	68.5	61.1	67.4	13.4	44.5	67.8	97.9

Median TSS's found throughout the SLRE in 2012 and 2013 (2012 – 10.1 mg/l, 2013 – 8.0 mg/l) (Bellinger et al. 2015) were generally lower than those found in Allouez and Pokegema Bays (10 – 33.3 mg/l) (Table 21). The bays are influenced by drainage from clay rich watersheds. Stream TSS data from the primary tributaries to Allouez and Pokegama Bay is shown in Table 22. Median stream TSS's ranged from 32 to 39 mg/l and were substantially higher than those for the bay sites, except for site PS which had a median TSS very similar to the Pokegama River. Partial sedimentation of tributary inputs of suspended solids would be expected in the bays. Frequent resuspension of partially sedimented inputs of clay and silt probably maintains the very noticeable turbidity in Allouez and Pokegama Bays throughout the season.

Resuspension results from wind generated waves, seiche-induced flow reversals, and biopedturbation, especially by bottom feeding fish.

TSS's for all bay site samples were moderately correlated with TP's ($R^2 = 0.71$) (Figure 48). However, for samples with TP's < 100 ug/l the correlation was much weaker ($R^2 = 0.22$) (Figure 49).

Figure 46. Bay Sites Total Suspended Solids Concentration Means



Error bars are 90% confidence intervals

Table 22. Total Suspended Solids Concentrations (mg/l) for Bay Tributaries

	Tributary Stream		
	Pokegama R.	Bear Ck.	Bluff Ck.
Mean:	75.0	66.6	106.3
Median:	32.1	39.2	38.5
Max.:	464	257	936
Min.:	10.8	15	12

Figure 47. Bay Sites Total Suspended Solids Concentrations

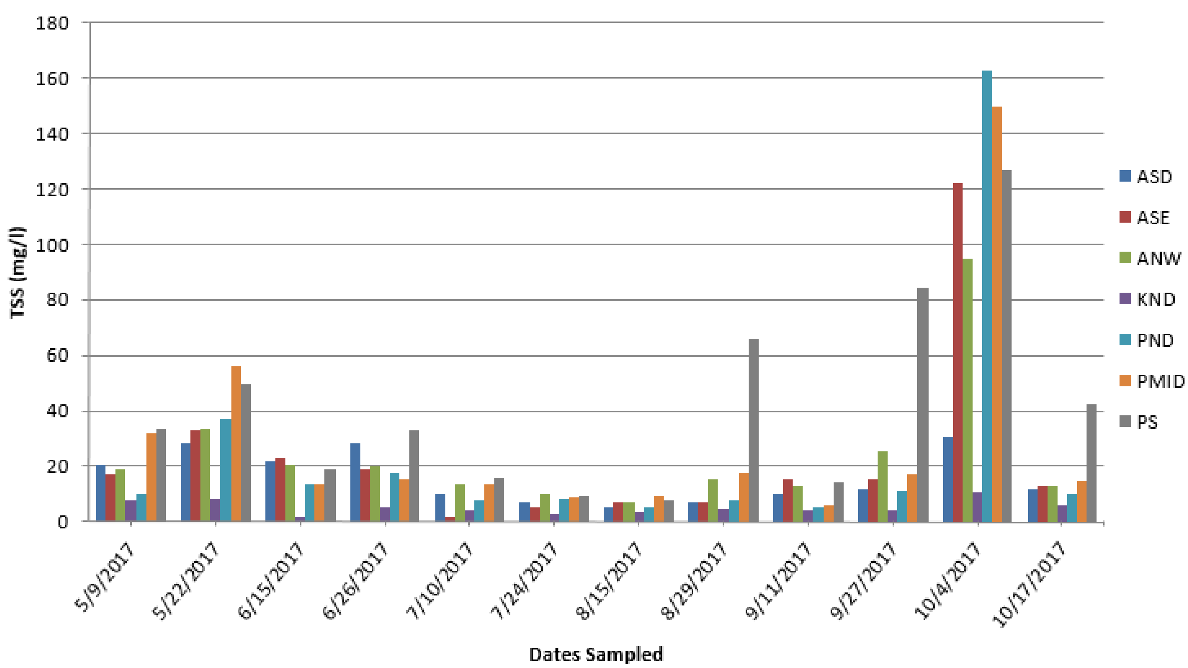


Figure 48. Bay Sites Total Phosphorus vs. Total Suspended Solids Relationship (for all data)

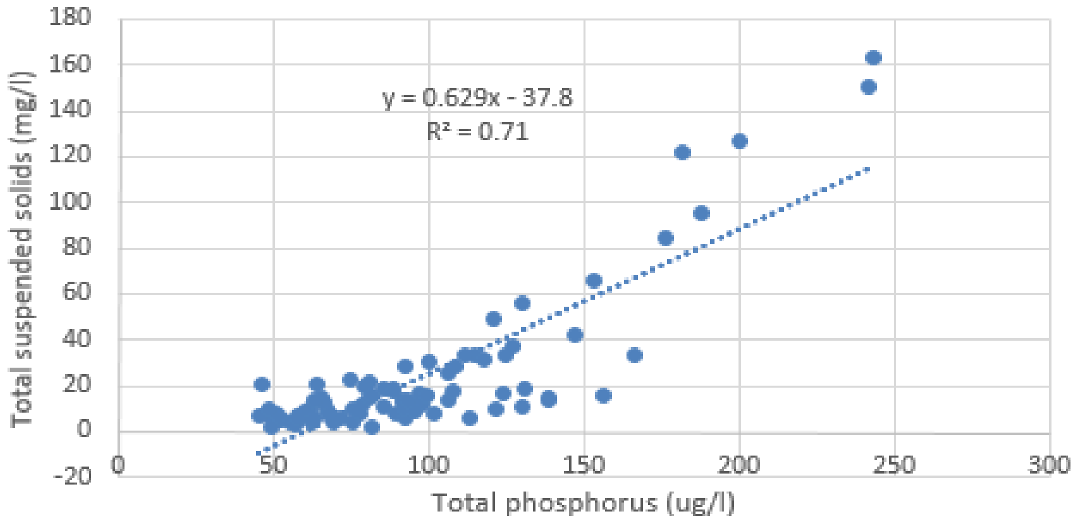
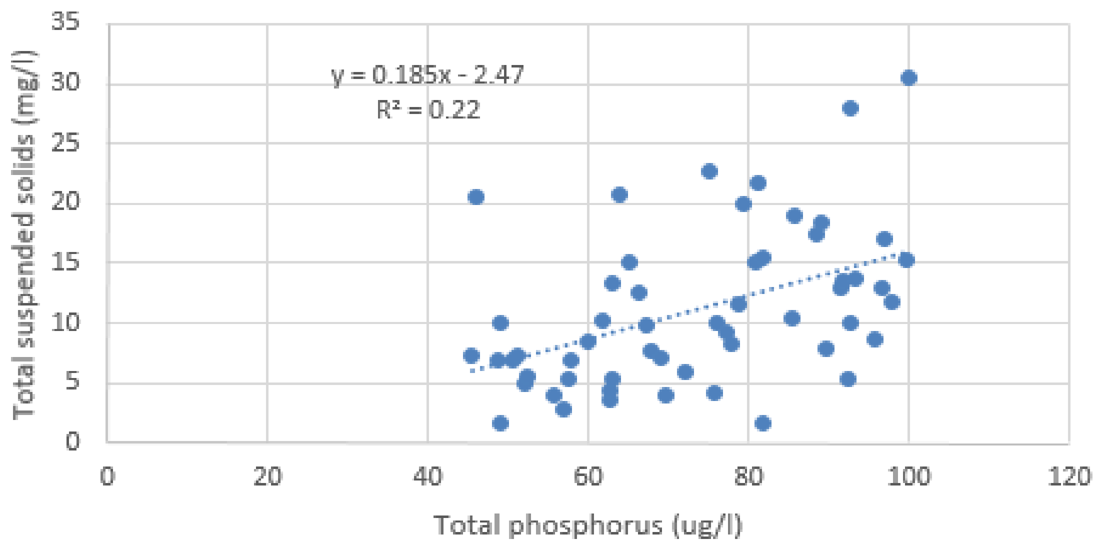


Figure 49. Bay Sites Total Phosphorus vs. Total Suspended Solids Relationship (for TP's < 100 ug/l)



Despite the relatively high TSS's in the bays, median values (Table 21) were at, or below the SLRE BUI TSS goal of 15 mg/l at five of the seven sites. Only sites ANW and PS had median values exceeding the goal. TSS's were highest in May and early October (Figure 47) when high rates of watershed runoff occurred (Figure 17). Site PS showed occasional TSS spikes in other months due to the strong influence of the Pokegama River. A Pokegama River flow spike that peaked on August 27th at 325 cfs accounted for the high TSS at site PS on August 29th when river flow was still 50.5 cfs.

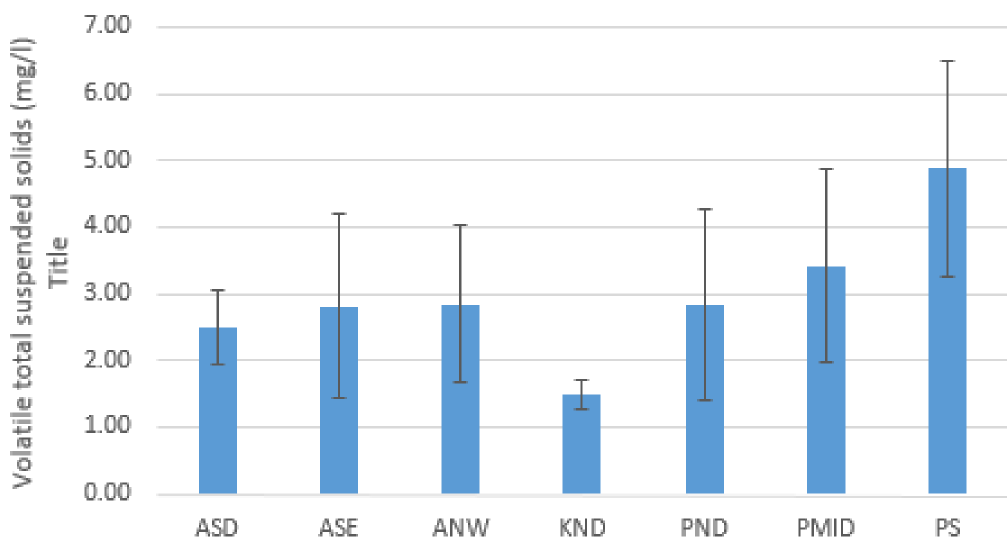
For Allouez and Pokegama Bays, 2017 TSS's were similar to those found in 2011-12 and 2012-13, but not 2007 (see "Comparison of 2017 TP's and Related Parameters to Data from Other Years").

Mean volatile total suspended solids concentrations (VTSS's) ranged from 1.49 mg/l (site KND) to 4.90 mg/l (site PS) (Figure 50). The mean VTSS for site KND was significantly lower than means for sites ASD, PMID, and PS. The mean VTSS for site PS was significantly higher than means for sites KND and ASD. The VTSS for site KND was probably lower due to the strong influence of SLRE water on that site. The mean VTSS for site PS was higher due to the strong influence of Pokegama River water on that site.

Median VTSS's (Table 21) were low, and a small percentage (11.4–36.0 %) of TSS's. This indicates the majority of TSS is inorganic material (such as clay and silt) rather than organic material (such as algae and detritus). VTSS measurements were below detection limits (2.0–6.3 mg/l) for 56% of samples. Values of one-half the detection limit were used for these samples, so statistics generated were somewhat inaccurate.

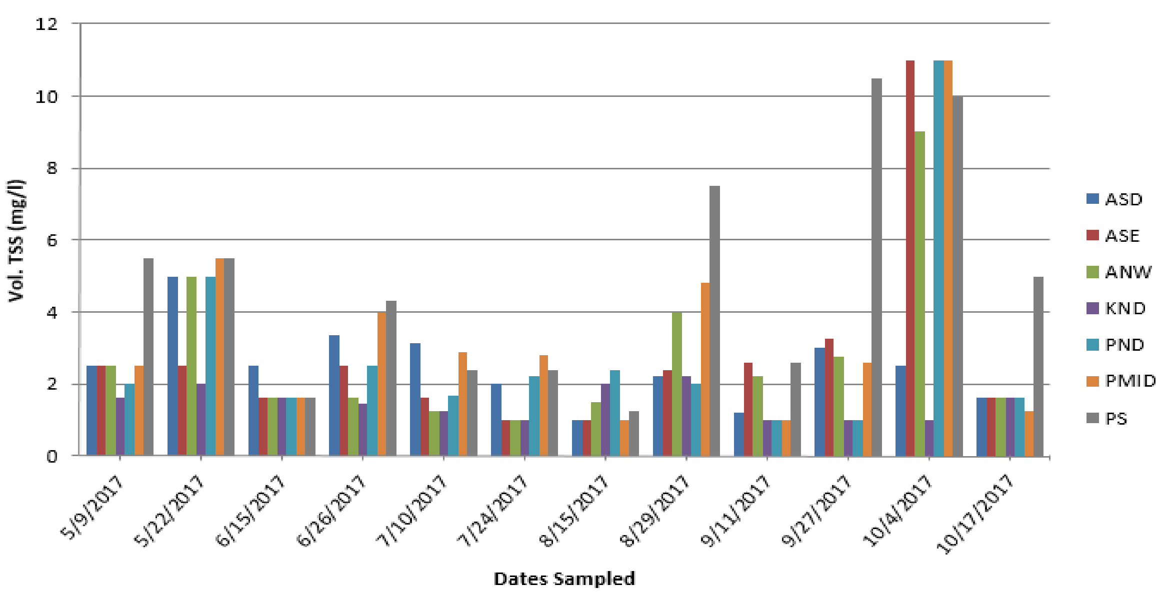
VTSS's appear to be roughly correlated with TSS (Figures 47 and 51). This suggests organic detritus delivered by runoff was a large component of VTSS. VTSS's appear to be very poorly correlated with CHL's (Figures 51 and 27), which suggests algae were a minor component of VTSS.

Figure 50. Bay Sites Volatile Total Suspended Solids Concentration Means



Error bars are 90% confidence intervals

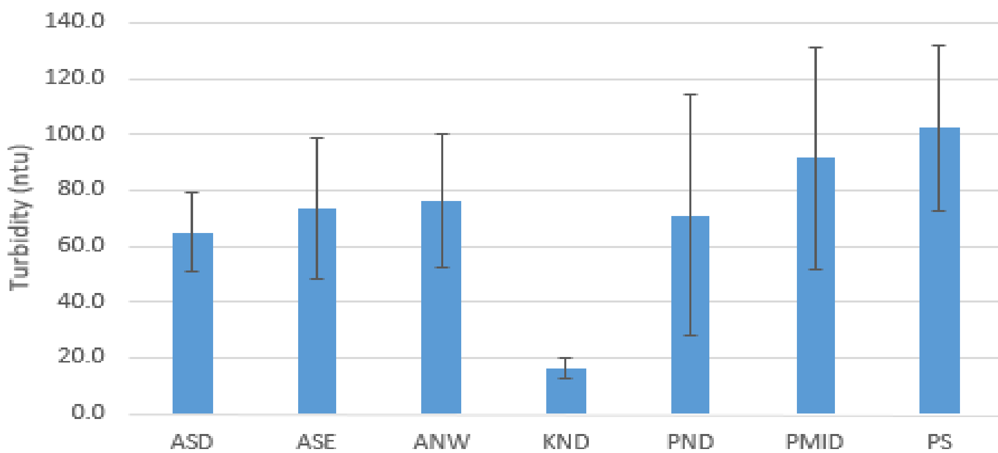
Figure 51. Bay Sites Volatile Total Suspended Solids Concentrations



Mean turbidities ranged from 16.4 ntu (site KND) to 102 ntu (site PS) (Figure 52). Site KND, which is strongly influenced by mixing with SLRE water had the lowest turbidity. Site PS, which is strongly influenced by Pokegama River water had the highest turbidity. Like TSS's, turbidities were highest in May and early October when high rates of watershed runoff occurred (Figure 53). Site PS showed occasional turbidity spikes in other months due to the strong influence of the Pokegama River.

For Allouez and Pokegama Bays, 2017 turbidities were similar to those found in 2011-12, and 2012-13 (see "Comparison of 2017 TP's and Related Parameters to Data from Other Years"). There is a strong correlation between turbidities and TSS's for all bay site samples ($R^2 = 0.90$) (figure 54). The correlation is weaker, but still moderate for samples with turbidities < 100 ntu's ($R^2 = 0.63$) (figure 55). Turbidity is a measure of light scattering by suspended particulates, while total suspended solids is a measure of the mass of suspended particulates, so a correlation would be expected. Clay particles produce more light scattering per unit mass than silt particles.

Figure 52. Bay Sites Turbidity Means



Error bars are 90% confidence intervals

Figure 53. Bay Sites Turbidities

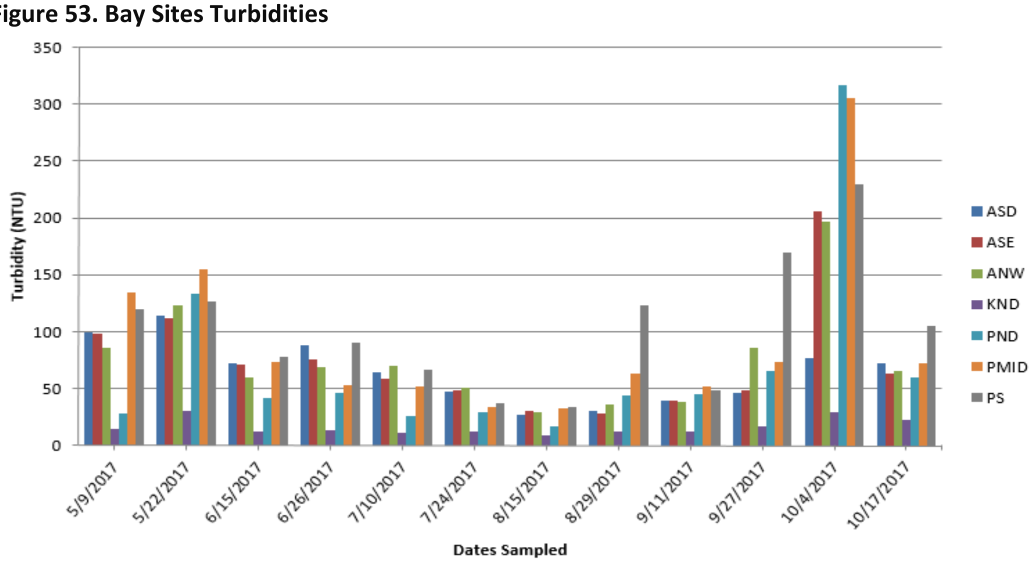


Figure 54. Bay Sites Turbidity vs Total Suspended Solids Relationship (for all data)

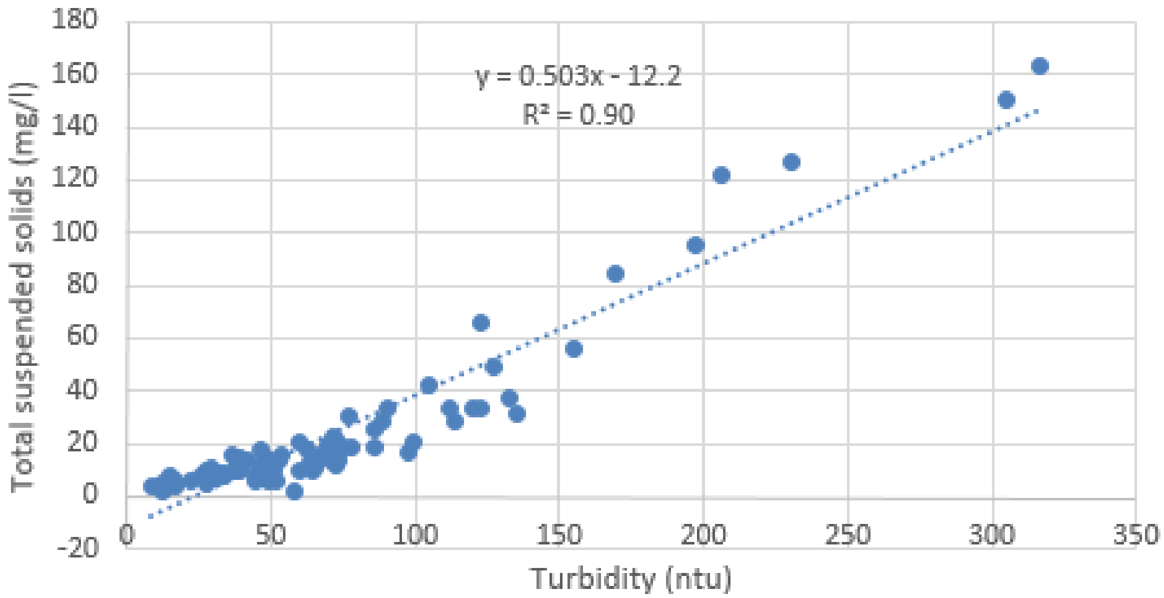
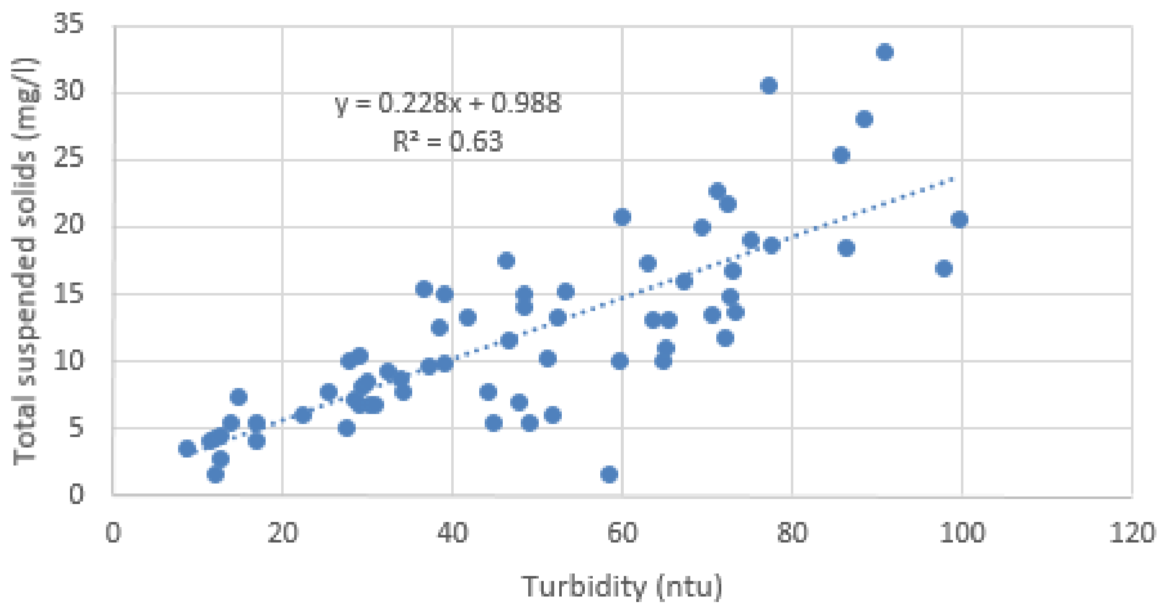


Figure 55. Bay Sites Turbidity vs Total Suspended Solids Relationship (for turbidities < 100 ntu)



Tributary Stream Results and Discussion

Stream Watershed Characteristics

Watershed Areas, Land Use, Sediment and Nutrient Sources

Watershed area and land use for the five monitored tributaries are shown in Table 23**.** The Pokegama River has the largest watershed (73.2 km^2), while the unnamed tributary at Billings Drive has the smallest watershed (4.1 km^2). Agricultural row crops are absent in four of the watersheds, and only account for 1.2% of land use in the Bear Creek watershed. Grassland (pasture and hayfields) is the largest agricultural land use and comprises 1.4 – 20.6% of the watersheds. Wetland is the most common land use in all watersheds, ranging from 39.9 – 73.4%.

All stream watersheds are located in the Lake Superior Clay Plain. Soils in the area are clay rich and highly erodible. Erosion to the Nemadji River, which is also strongly influenced by clay plain soils, has been extensively assessed, and those findings are probably applicable to other clay plain streams. For the Nemadji River, eroding bluffs along streams were estimated to be the source of 98% of the fine sediment reaching the stream mouth. Roadside erosion, and sheet and rill erosion, were each estimated to be the source of an additional 1% of fine sediment (NRCS 1998). A second erosion estimate for the Nemadji River estimated that 89% of fine sediment originated from streambank and bluff erosion along streams (Carlton County 2002). A third erosion assessment for the Nemadji River estimated that channel erosion provides 75% of the total sediment load at the stream mouth, and upland erosion provides 25% of the load (Butcher 2016). Natural background sources account for 55% of the upland erosion (Butcher 2016). These conditions make sediment control for clay plain streams difficult.

Streambank and bluff erosion along streams is believed to be the largest source of total suspended solids to bay tributary streams. However, it is not believed to be a large phosphorus source (Bahnick 1977).

Four-site composite samples of eroding stream bank soil were collected from both Bear and Bluff Creeks (Roesler 2018). The samples had a mean TP concentration of 472 mg /kg (range = 454-491 ug/l). Bear and Bluff Creeks had a mean TP concentration of 198 ug/l and a mean TSS concentration of 86 mg/l. Adjusting the TSS concentration for volatile TSS (-14%; from riverine bay site PS data) gives a non-volatile TSS concentration of 74 mg/l. This data suggests that, at most, stream bank erosion could be supplying 18% of the mean stream TP concentration for Bear and Bluff Creeks (if all non-volatile TSS is supplied by stream bank erosion).

Watershed non-point sources of phosphorus include pasture and hayfield runoff (including the influence of manure spreading), barnyards, and septic systems. The low infiltration rates and high runoff rates of clay plain soils are likely to limit the retention of phosphorus by soils.

The Village of Superior wastewater lagoon outfall is a point source of phosphorus for the Pokegama River. That discharge is about 5.7 % of the Pokegama River's May-October TP load (see "Total Phosphorus" section below).

Table 23. Tributary Stream Watershed Areas and Land Use

	Tributary Streams and Receiving Bays				
	Alllouez Bay			Kimballs Bay	Pokegama Bay
	Bear Creek	Bluff Creek	Unnamed @ Moccasin Mike Rd	Unnamed @ Billings Drive	Pokegama River
Watershed Area (km2)	24	50.6	6.6	4.1	73.2
Land Use %					
Urban or developed	8.2	2.7	9.1	3.8	3.9
Agriculture (Row Crops)	1.2	0	0	0	0
Grassland (Pasture, Hay)	13	20.6	4.8	1.4	9.2
Forest	16.3	36.8	15.8	20.8	30.2
Open Water	0.1	0.1	0	0.6	0.2
Wetland	61.3	39.9	70.4	73.4	56.5
Barren	0	0	0	0	0
Shrubland	0	0	0	0	0

Figure 56. Eroding Clay Banks along a Well Vegetated Section of the Pokegama River

Point Sources

The Village of Superior wastewater lagoon outfall discharges to the Pokegama River. There are no point source discharges to Bear or Bluff Creeks or the two unnamed streams.

Streamflow in 2017

The clay-rich watershed soils have low infiltration rates and high runoff rates. Streamflow is flashy with most flow produced by runoff events. Measured flows for the Pokegama River during May – October of 2017 are shown in figure 57 (Complete daily mean stream flows are contained in appendix 3). Monthly rainfall was below normal in June, July, and September, and above normal in May, August, and October. Total rainfall during May-October of 2017 was 15% above normal (Table 24).

Figure 57. Pokegama River Flows (data from USGS)

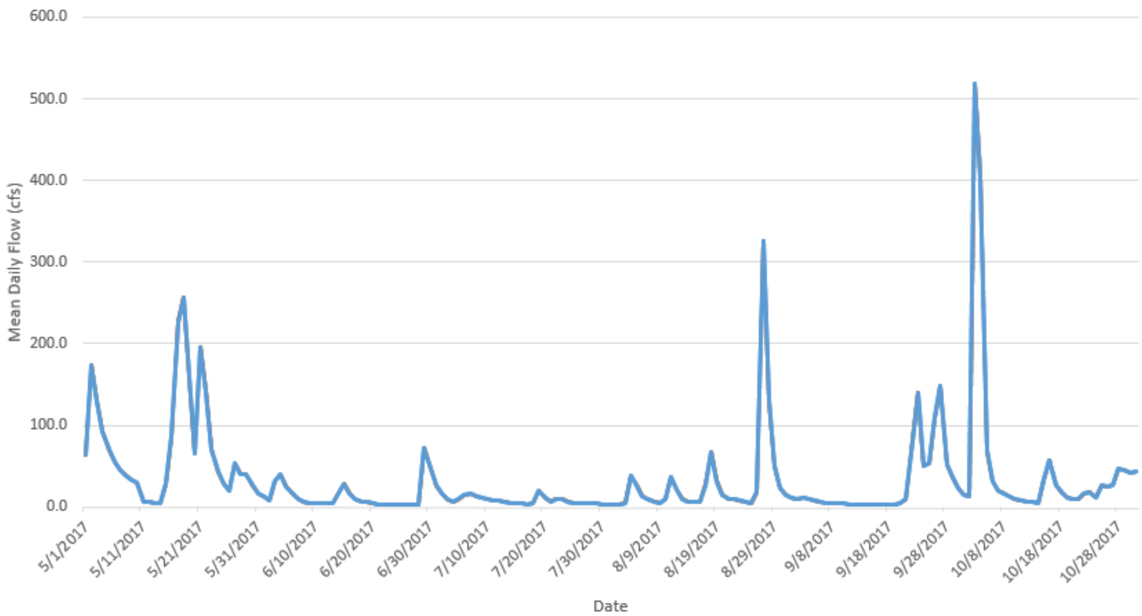


Table 24. Monthly Precipitation for May-October 2017

	2017	
Months	Total Precip. (in)	Avg. Precip. (in)
May	5.03	3.13
June	2.66	4.1
July	3.01	3.95
August	7.4	3.76
September	2.95	4.11
October	4.34	3.01
May-Oct	25.39	22.06
May-Oct 2017 difference from average	15%	

Note: - Avg Precip data obtained from Superior WI station USC00478349
Note: - Precip, cumulative precip, and total precip data obtained from NOAA National Estuarine Research Reserve System, Pokegama Bay weather station LKSPOMET

Table 25 shows the number of bay volumes of water that are delivered to the bays by drainage from their direct watersheds during May through October. This provides an indication of how strongly water quality in the bays is influenced by direct watershed drainage versus seiche-induced backflows of St. Louis River and/or Lake Superior water. Kimballs Bay had the lowest relative delivery of direct watershed water, with only 0.8 bay volumes of water delivered over the six-month period. Kimballs Bay was more strongly influenced by seiche-induced backflows. Pokegama Bay had the highest relative delivery of direct watershed water, with 6.9 bay volumes of water delivered. Pokegama Bay was more strongly influenced by direct watershed runoff than the other two bays.

Table 25. Bay Volumes of Water Delivered by Direct Watersheds May-October 2017

Bay	Area (acres)	Estimated Mean Depth (ft)	Volume (acre-ft)	Direct Watershed Area (km2)	May-Oct Bay Volumes Delivered by Direct Watershed*
Allouez	1011	6	6066	82.4	2.3
Pokegama	441	5	2205	89.3	6.9
Kimballs	101	12	1212	5.6	0.8

**Watershed flows assumed to be area-proportional to measured Pokegama River flows.*

Field Parameter Results

Table 26 shows the summarized field monitoring results for the three named tributary stream sites. Table 27 shows the summarized field monitoring results for the two unnamed tributary stream sites. Figures 58 through 62 display means and 90% confidence intervals for field parameters from all five stream sites. The primary (named) streams were monitored 4x/month, while the unnamed streams were monitored 1x/month. The mean flow for the dates the unnamed streams were monitored was about half the mean flow for all dates the named streams were sampled. This needs to be considered when comparing named and unnamed streams for water quality field parameters that are significantly correlated with flow (turbidity and conductivity).

Table 26. Field Parameter Data for Named Streams

PRIMARY STREAM FIELD MONITORING PARAMETERS							
Stream	Statistic	Temp. (°C)	D.O. (mg/l)	pH (s.u.)	Conductivity (umhos/cm)	Turbidity (ntu)	Transparency Tube (cm)
BEAR CREEK	Mean:	13.4	9.7	7.6	183	142	9
	Median:	14	9.4	7.7	170	123	10
	Max.:	19.4	12.3	8	328	315	16
	Min.:	6.5	8.1	6.9	81	83	3
BLUFF CREEK	Mean:	13.5	8.7	7.6	178	218	8
	Median:	14.4	8.2	7.6	168	145	9
	Max.:	19.6	11.7	7.9	330	879	13
	Min.:	6.9	6.2	7.1	91	105	1.5
POKEGAMA RIVER	Mean:	14.2	9.2	7.7	168	138	11
	Median:	14.9	9.1	7.7	173	106	10
	Max.:	21.6	12.1	8	258	475	24
	Min.:	7.1	4.9	7.3	86	49	2

Named streams were monitored 4x per month, May through October. Conductivity is specific conductance.

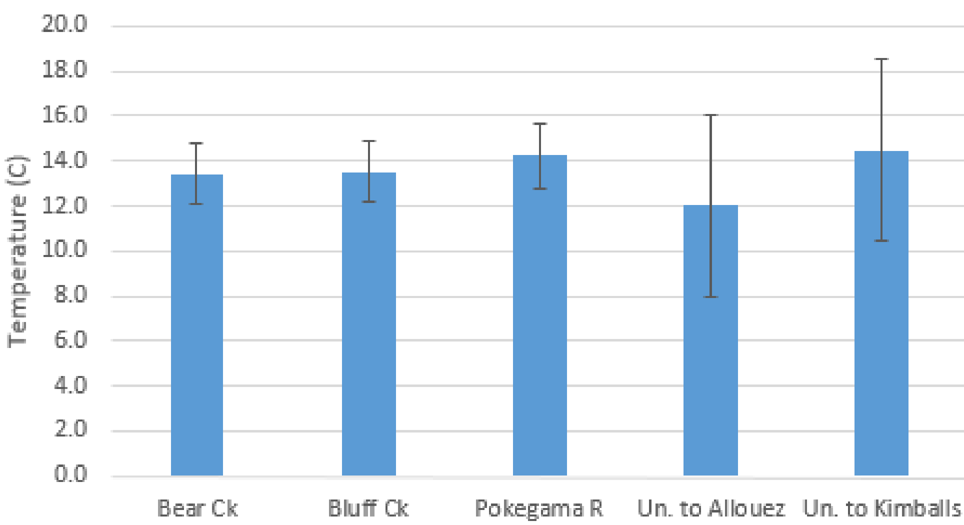
Table 27. Field Parameter Data for Unnamed Streams

	UNNAMED STREAM FIELD MONITORING PARAMETERS						
Stream	**Statistic**	**Temp. (°C)**	**D.O. (mg/l)**	**pH (s.u.)**	**Conductivity (umhos/cm)**	**Turbidity (ntu)**	**Transparency Tube (cm)**
Unnamed tributary to Allouez Bay at Moccasin Mike Rd.	Mean:	12	9.6	7.4	357	98	13
	Median:	13.8	9.1	7.6	378	95	12
	Max.:	16.4	12.2	7.8	491	123	20
	Min.:	5.9	7.4	6.6	204	63	9
Unnamed tributary to Kimballs Bay at Billings Drive	Mean:	14.5	6.7	7.5	211	84	15
	Median:	16.1	6.2	7.4	233	74	17
	Max.:	19.5	11.5	7.7	289	145	22
	Min.:	7.4	3.8	7.3	113	48	8

Unnamed streams were monitored 1x per month, May through October. Conductivity is specific conductance.

Mean stream temperatures ranged from 12°C (unnamed tributary to Allouez Bay) to 14.5 °C (unnamed tributary to Kimballs Bay). Mean stream temperatures for all sites were not significantly different (Figure 58). While the seasonal mean temperature for the unnamed tributary to Allouez Bay was not significantly different, the site had the coolest temperature on five of the six dates of monitoring. This suggests that this tributary has greater groundwater inputs than the other streams.

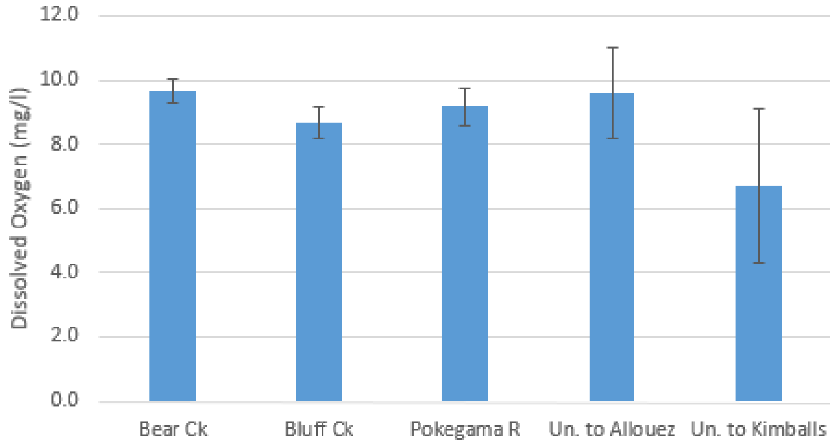
Figure 58. Stream Temperature Means



Error bars are 90% confidence intervals

Mean dissolved oxygen concentrations (D.O.'s) ranged from 6.7 mg/l (unnamed tributary to Kimballs Bay) to 9.7 mg/l (Bear Creek) (Tables 26 and 27). Mean D.O.'s for Bear Creek were significantly higher than for Bluff Creek and the unnamed tributary to Kimballs Bay (Figure 59). One measurement for the Pokegama River (4.9 mg/l) was just below the 5 mg/l water quality standard. The unnamed tributary to Kimballs Bay had two of six dates with D.O.'s less than 5 mg/l (July 19th – 3.8 mg/l; Sept 20th – 4.1 mg/l). That stream site is fringed with wetlands and subject to seiche-induced backflows.

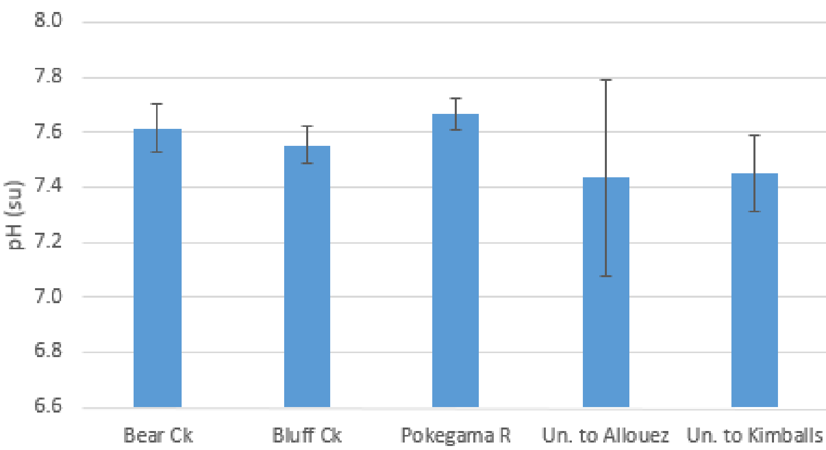
Figure 59. Stream Dissolved Oxygen Concentration Means



Error bars are 90% confidence intervals

Mean pH's for all streams were similar and ranged from 7.4 (unnamed tributary to Allouez Bay) to 7.7 (Pokegama River) (Tables 26 and 27), with no significant differences between streams (Figure 60).

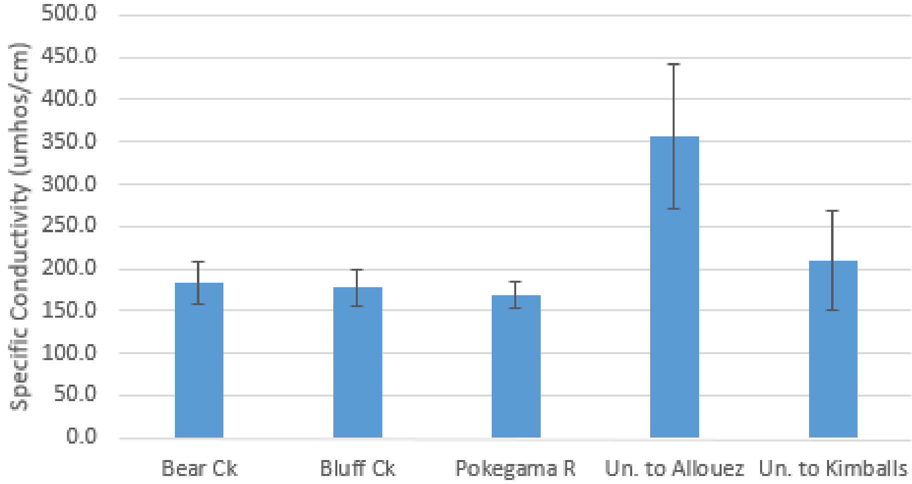
Figure 60. Stream pH Means



Error bars are 90% confidence intervals

Mean conductivities (specific conductance) ranged from 168 umhos/cm (Pokegama River) to 357 umhos/cm (unnamed tributary to Allouez Bay) (Tables 26 and 27). The mean conductivity for the unnamed tributary to Allouez Bay was significantly higher than all other sites (Figure 61). This, along with cooler temperatures, suggests greater groundwater inputs to this stream. However, the high conductivities could also be influenced by the high density of highway road surfaces in the watershed. There are 1.6 km of 2-lane highway per km2 of watershed. State highways 2/53 and 13, and County Highways Z and UU are present. Chloride from road salt could be a contributor to stream conductivities if there is a lag time (winter to summer) in chloride transport through the watershed. Conductivity was moderately inversely correlated with stream flow (Pokegama R R^2 = 0.66, Bear Ck R^2 = 0.60, Bluff Ck R^2 = 0.67). The higher mean conductivity at this site was probably also influenced by the lower flows on the dates sampled, when groundwater inputs (with high conductivity) supply a greater portion of the flow.

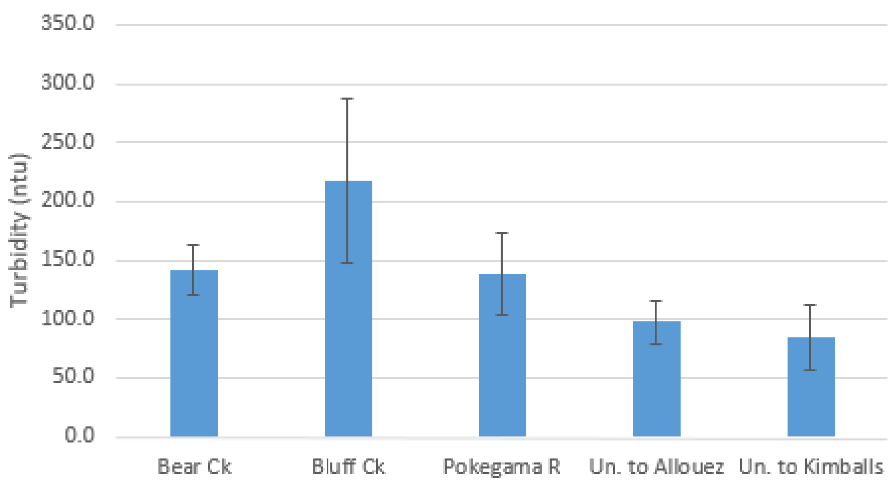
Figure 61. Stream Conductivity Means



Error bars are 90% confidence intervals

Mean turbidities ranged from 84 ntu (unnamed tributary to Kimballs Bay) to 218 ntu (Bluff Creek) (Tables 26 and 27). Mean turbidities for the unnamed tributary to Allouez Bay and the unnamed tributary to Kimballs Bay were significantly lower than means for Bear and Bluff Creek, but not for the Pokegema River (Figure 62). The watersheds for the two unnamed streams have the highest percentages of wetlands (70.4%, 73.4%) and the lowest percentages of grassland (pasture, hay) (1.4%, 4.8%) (Table 23). This may have contributed to the lower turbidities. Turbidity was poorly to highly correlated with stream flow (Pokegama R R^2 = 0.87, Bear Ck R^2 = 0.34, Bluff Ck R^2 = 0.03). The lower mean turbidities at the unnamed sites may also have been influenced by the lower flows on the dates sampled, since less runoff (with high turbidity) was contributing to stream flow.

Figure 62. Stream Turbidity Means



Error bars are 90% confidence intervals

Lab Parameter Results

Table 28 shows the summarized lab testing results for the three named tributary stream sites. Table 29 shows the summarized lab testing results for the two unnamed tributary stream sites. Complete data for tributary streams is contained in appendix 2. Stream water quality parameter means are shown in figures 63, 65, 67, 69, 71, 73, 75, and 79. Trends for stream water quality parameters at the three named tributary stream sites are shown in figures 64,66, 68, 70, 72, 74, 76, and 80. The lower mean flow for the dates the unnamed streams were monitored needs to be considered when comparing unnamed and named streams for water quality lab parameters that are significantly correlated with flow (total phosphorus, total suspended solids, total Kjeldahl nitrogen).

Table 28. Lab Parameter Data for Named Streams

PRIMARY STREAM LAB RESULTS									
Stream	Statistic	TP (µg/l)	OP (µg/l)	TSS (mg/l)	NH_3-N (µg/l)	$NO_3 + NO_2$-N (µg/l)	TKN (mg/l)	Iron (mg/l)	BOD (mg/l)
BEAR CREEK	Mean:	173	24	67	50	85	1.38	4.1	1.8
	Median:	145	21	39	46	74	1.45	4.1	1.8
	Max.:	364	64	257	145	216	1.89	5.7	3.9
	Min.:	96	12	15	15.5	9.5	0.11	3.2	1
BLUFF CREEK	Mean:	224	24	106	42	79	1.46	4.9	2.3
	Median:	170	23	39	44	57	1.50	4.2	1.6
	Max.:	987	45	936	68	259	2.41	9.9	5.5
	Min.:	107	12	12	22	18	0.85	3.0	1
POKEGAMA RIVER	Mean:	182	31	75	42	49	1.52	3.9	1.8
	Median:	161	20	32	41	42	1.51	2.8	1.5
	Max.:	514	154	464	86	152	2.19	8.3	3.4
	Min.:	103	10	11	16	9.5	0.83	2.5	1

TP = total phosphorus; OP = orthophosphate phosphorus; TSS = total suspended solids; NH_3 - N = ammonia nitrogen; NO_3+NO_2- N= nitrate plus nitrite nitrogen; TKN = total Kjeldahl nitrogen; BOD = 5-day biochemical oxygen demand.
Named streams were monitored 4x per month, May through October.

Table 29. Lab Parameter Data for Unnamed Streams

UNNAMED STREAM LAB RESULTS							
Stream	Statistic	TP (µg/l)	OP (µg/l)	TSS (mg/l)	NH_3-N (µg/l)	$NO_3 + NO_2$-N (µg/l)	TKN (mg/l)
Unnamed tributary to Allouez Bay at Moccasin Mike Rd.	Mean:	106	11.6	28.3	43.4	82.2	1.57
	Median:	110	11.9	24.7	42.6	55.9	1.61
	Max.:	129	13.8	53.7	57.4	178	1.94
	Min.:	66.9	7.9	9.2	30.8	9.5	1.16
Unnamed tributary to Kimballs Bay at Billings Drive	Mean:	160	32.7	30.4	37.1	39.1	1.30
	Median:	169	34.4	16.7	41.5	13.75	1.14
	Max.:	204	47.3	82.7	57.7	95.8	2.06
	Min.:	77.9	11.2	7.2	7.5	9.5	1.08

Unnamed streams were monitored 1x per month, May through October.

Total Phosphorus

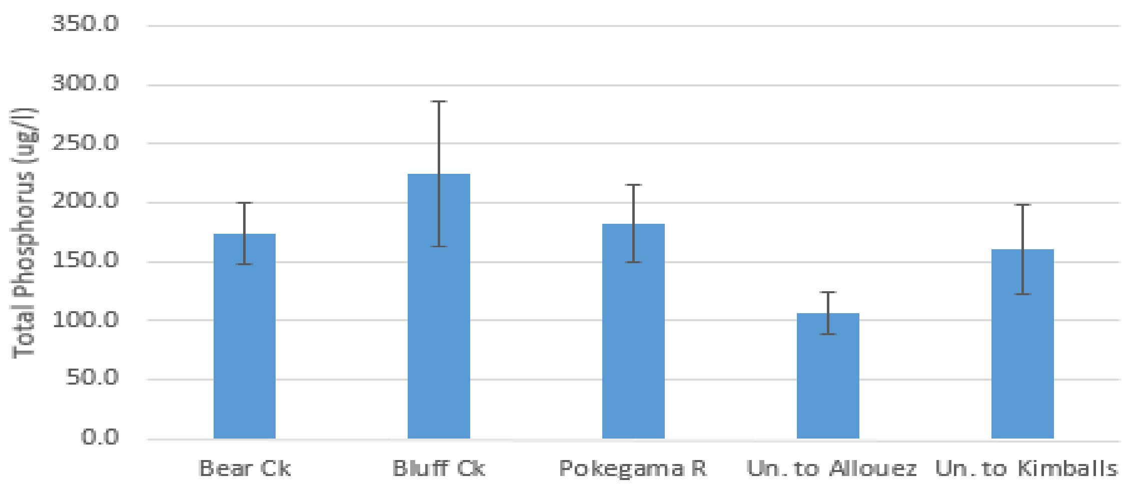
Mean total phosphorus concentrations (TP's) ranged from 106 ug/l (unnamed to Allouez Bay) to 224 ug/l (Bluff Creek) (Tables 28 and 29). TP's exceeded the 75 ug/l WI DNR stream standard at all sites on all dates, except for one sample from the unnamed tributary to Allouez Bay (May 3rd; 66.9 ug/l). The mean TP for the unnamed tributary to Allouez Bay was significantly lower than for the named streams. At least part of this difference may have been due to the lower mean flows on the dates the unnamed streams were sampled, since TP was poorly to moderately correlated with stream flow (Pokegama R R^2 = 0.53, Bear Ck R^2 = 0.13, Bluff Ck R^2 = 0.45).

A large TP spike was evident for Bluff creek on June 29th (Figure 64). A relatively minor flow spike occurred on the Pokegama River on that date (Figure 57) and precipitation of 1.3 inches was reported. Localized precipitation may have differed. There is a cattle raising operation with a large area of pastured slopes and stream channels in the upper Bluff Creek watershed. There is also a dairy farm located on a Bluff Creek tributary (Birch Creek). These are ~~is one~~ possible sources of this spike.

A large TP spike was evident for the Pokegama River on October 3rd (figure 64). The highest flow of the season occurred on the Pokegama River on that date (Figure 57) and the river was flowing out of its banks. Streambank erosion during this peak flow may have been a source. Additionally, construction of an oil pipeline across the river over the previous months had left some areas of soil not fully stabilized, which may also have contributed to the TP spike.

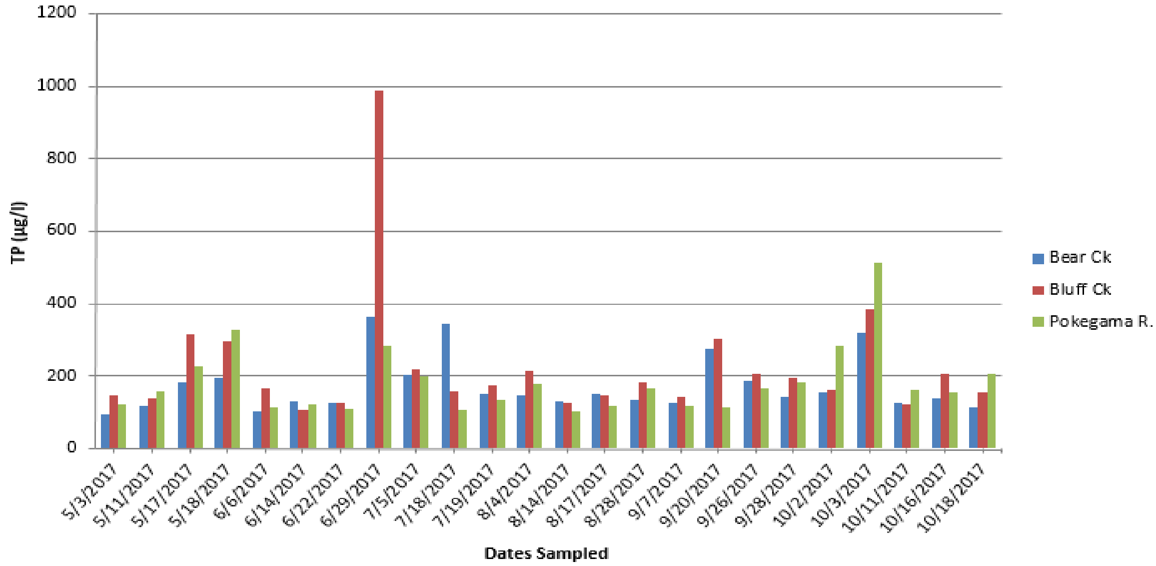
The 2017 May-October TP load for the Pokegama River was 3,302 kg. The Village of Superior wastewater lagoons discharged 190 kg of TP to the river during that period. The discharge was about 5.7 % of the river's May-October TP load.

Figure 63. Stream Total Phosphorus Concentration Means



Error bars are 90% confidence intervals

Figure 64. Stream Total Phosphorus Concentrations

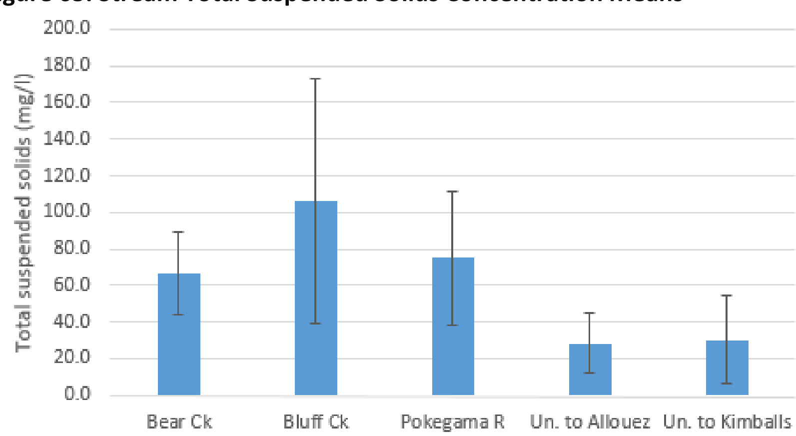


Total Suspended Solids

Mean total suspended solids concentrations (TSS's) ranged from 28.3 mg/l (unnamed tributary to Allouez Bay) to 106 mg/l (Bluff Creek) (Tables 28 and 29). There were no significant differences between site means (Figure 65). TSS was poorly to highly correlated with stream flow (Pokegama R $R^2 = 0.93$, Bear Ck $R^2 = 0.17$, Bluff Ck $R^2 = 0.11$).

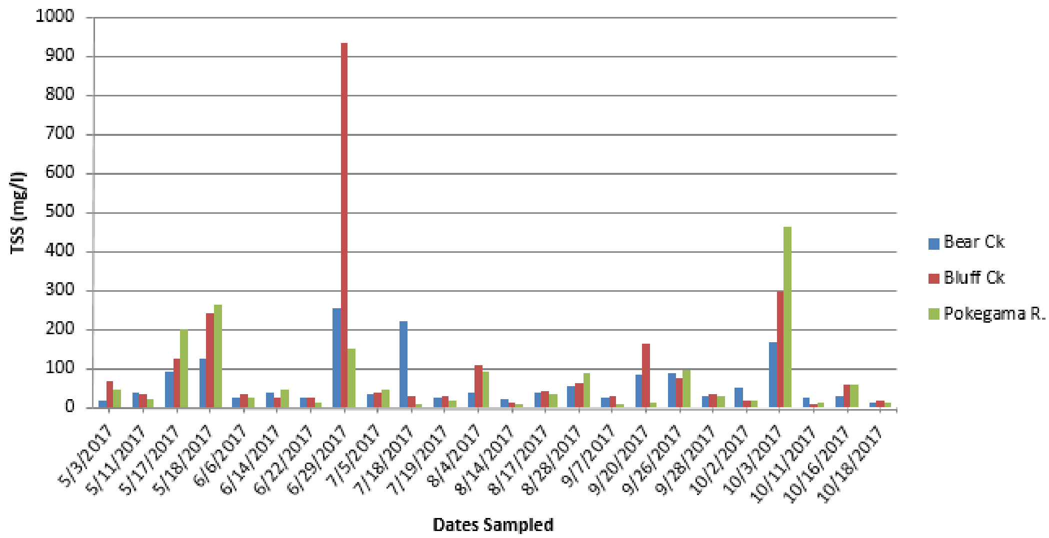
Similar to TP, a large TSS spike was evident for Bluff creek on June 29th (Figure 66). A relatively minor flow spike occurred on the Pokegama River on that date (Figure 57) and precipitation of 1.3 inches was reported. Localized precipitation may have differed. A cattle raising operation with a large area of pastured slopes and stream channels in the upper Bluff Creek watershed is one possible source of this spike.
Also similar to TP, a large TSS spike was evident for the Pokegama River on October 3rd (Figure 66). The highest flow of the season occurred on the Pokegama River on that date (Figure 57) and the river was flowing out of its banks. Streambank erosion during this peak flow event may have been a source. Additionally, construction of an oil pipeline across the river over the previous months had left some areas of soil not fully stabilized, which may also have contributed to this spike.

Figure 65. Stream Total Suspended Solids Concentration Means



Error bars are 90% confidence intervals

Figure 66. Stream Total Suspended Solids Concentrations



Orthophosphate

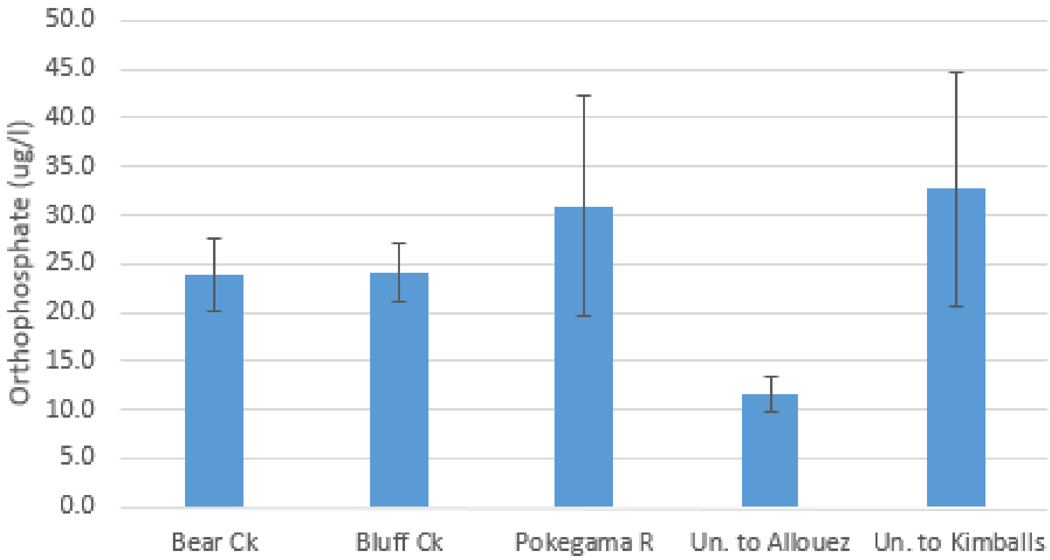
Mean orthophosphate concentrations (OP's) ranged from 11.6 ug/l (unnamed tributary to Allouez Bay) to 32.7 ug/l (unnamed tributary to Kimballs Bay) (Tables 28 and 29). The OP mean for the unnamed tributary to Allouez Bay was significantly lower than all other sites.

Suspended red clay in the SLRE area has been shown to adsorb OP when high concentrations occur (Bahnick 1980). OP is adsorbed by suspended clay when an equilibrium concentration of 20 - 42 ug/l is exceeded. Mean OP's (12.6 – 32.7 ug/l) were within or below this concentration range, suggesting suspended clay may be responsible for maintaining lower OP's.

The Pokegama River showed notable OP spikes on May 11th, and October 2nd, 11th, and 18th, with concentrations as high as 154 ug/l (Figure 68). The Village of Superior wastewater lagoons were discharging on all these dates and were the likely source of the OP spikes. Pokegama River flows were relatively low (4.9 – 17.7 cfs) on all dates with OP spikes, so there was limited dilution of lagoon discharge.

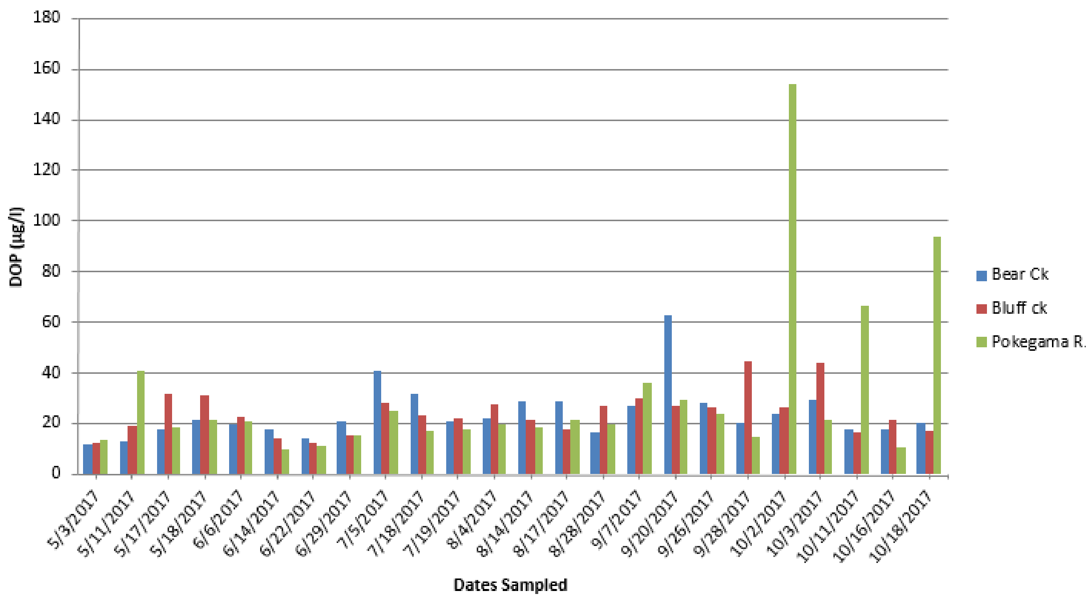
Bear Creek showed notable OP spikes on July 5th and September 20th. Stream flows were low on both these dates (2.9 and 1.6 cfs, respectively). Septic system discharge may have been the source of these spikes. Septic system influence tends to be more noticeable during low flow conditions when less dilution water is available. Failing septic systems have previously been found in the Bear Creek watershed. The Town of Parkland Sanitary District was formed to deal with failing septic systems in a portion of the watershed. The District installed sewers to collect household wastewater, which is partially treated and pumped to the City of Superior wastewater treatment plant for final treatment.

Figure 67. Stream Orthophosphate Concentration Means



Error bars are 90% confidence intervals

Figure 68. Stream Orthophosphate Concentrations

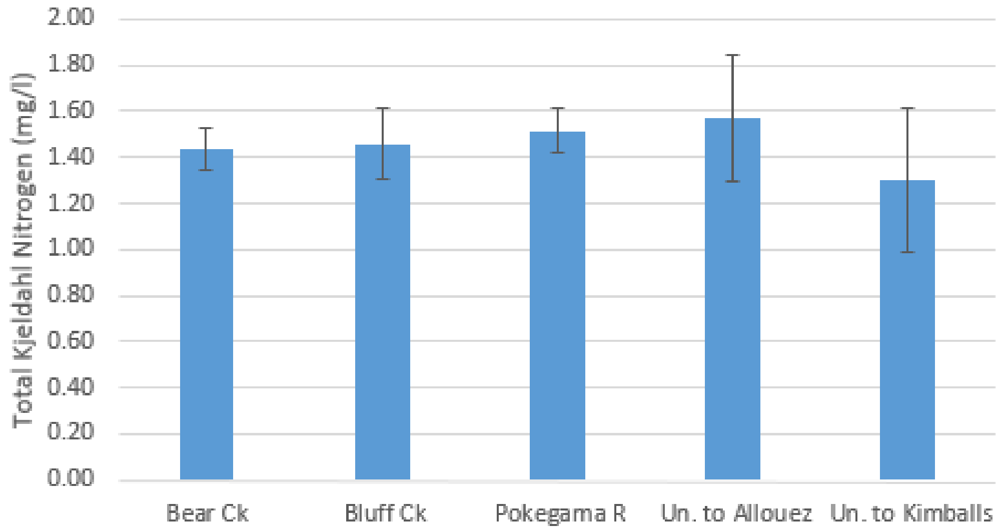


Total Kjeldahl Nitrogen

Mean total Kjeldahl nitrogen concentrations (TKN's) ranged from 1.30 mg/l (unnamed tributary to Kimballs Bay) to 1.57 mg/l (unnamed tributary to Allouez Bay) (Tables 28 and 29). There were no significant differences between site TKN means (Figure 69). TKN was weakly correlated with stream flow (Pokegama R R^2 = 0.26, Bear Ck R^2 = 0.12, Bluff Ck R^2 = 0.29).

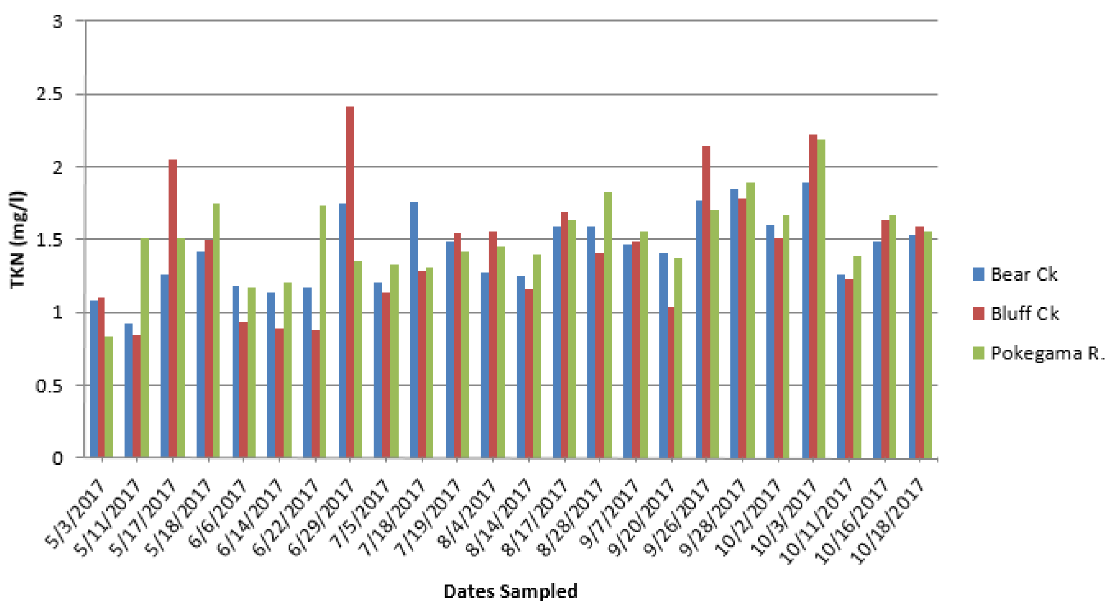
Bluff Creek had four dates when TKN's exceeded 2 mg/l (Figure 70). Stream flow on these dates averaged much higher than the mean flow for all sampled dates.

Figure 69. Stream Total Kjeldahl Nitrogen Concentration Means



Error bars are 90% confidence intervals

Figure 70. Stream Total Kjeldahl Nitrogen Concentrations



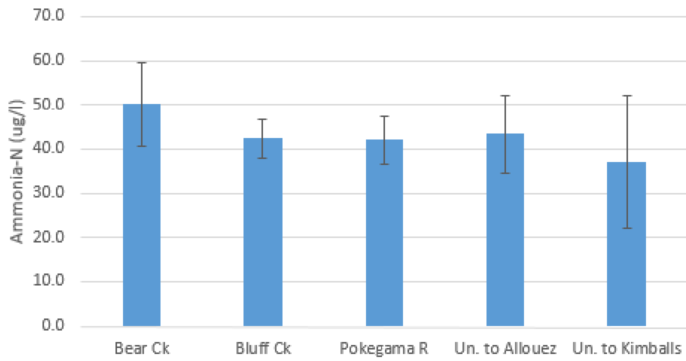
Ammonia Nitrogen

Mean ammonia nitrogen concentrations (NH_3's) ranged from 37.1 ug/l (unnamed tributary to Kimballs Bay) to 50 ug/l (Bear Creek) (Tables 28 and 29). There were no significant differences between site NH_3 means (Figure 71). NH_3's were not significantly correlated with stream flows.

NH_3's > 80 ug/l occurred in Bear Creek on 3 dates (Figure 72). These three dates had low stream flows (1.6 – 2.9 cfs). This suggests that septic systems may have been the source of these elevated NH_3's, as the elevated OP's during low stream flows also suggested.

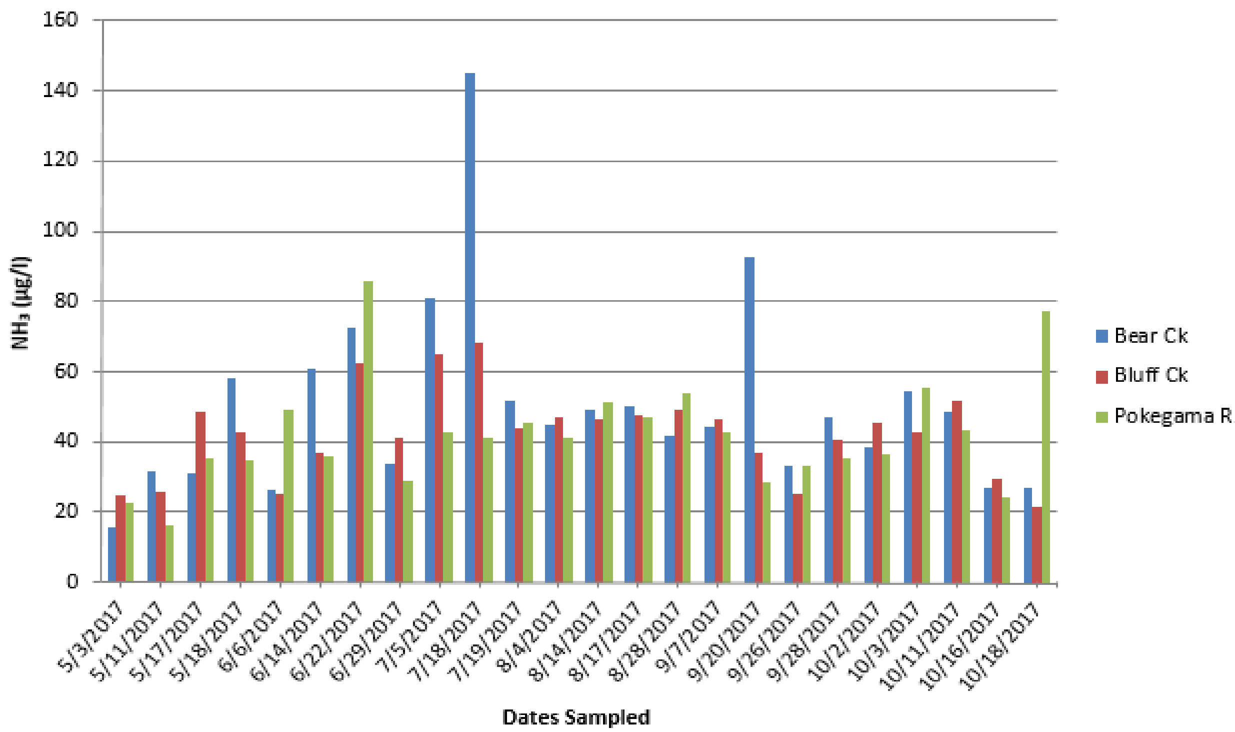
NH_3's > 75 ug/l occurred in the Pokegama River on 2 dates (Figure 72) with relatively low stream flows. The elevated NH_3 on October 18th can be fully accounted for by the Village of Superior wastewater lagoon discharge reported for that time period. Lagoon discharge reportedly was not occurring on June 22nd, the other date with elevated NH_3 in the Pokegama River. NH_3's for Bear and Bluff Creek were also relatively high on that date.

Figure 71. Stream Ammonia-N Concentration Means



Error bars are 90% confidence intervals

Figure 72. Stream Ammonia-N Concentrations

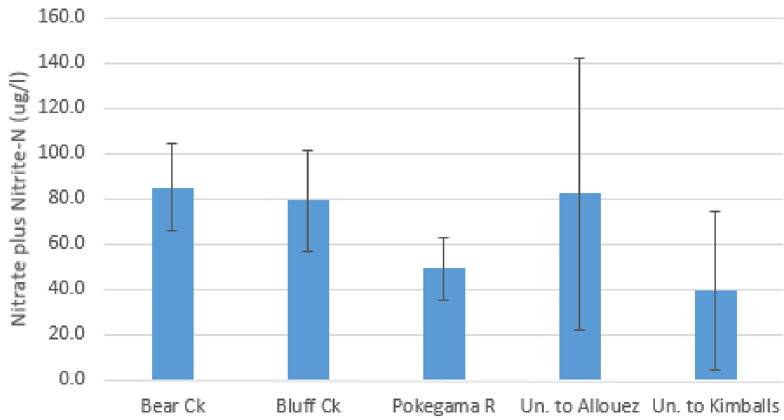


Nitrate plus Nitrite Nitrogen

Mean nitrate plus nitrite nitrogen concentrations (NO_x's) ranged from 39.1 ug/l (unnamed tributary to Kimballs Bay) to 85 ug/l (Bear Creek) (Tables 28 and 29). The mean NO_x for the Pokegama River was significantly lower than for Bear Creek. There were no other significant differences between site NO_x means (Figure 73). NO_x's were not significantly correlated with stream flows.

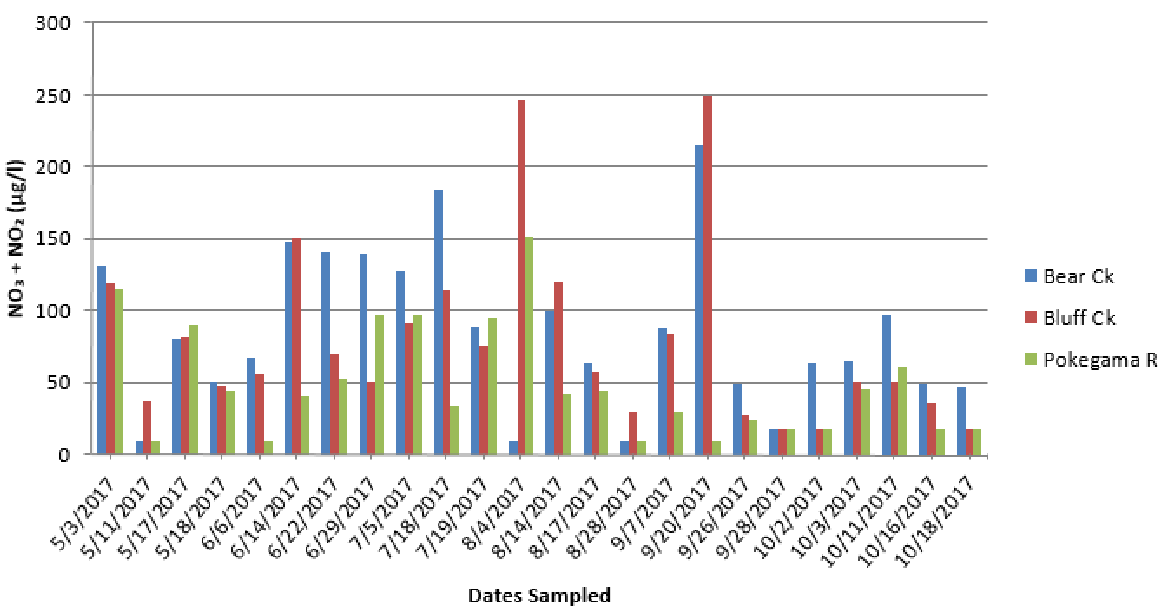
Bluff Creek had NO_x's > 200 ug/l on two dates (Figure 74). Stream flows were low to moderate on those dates and no specific source is suggested. Bear Creek had NO_x's > 175 ug/l on two dates. Both dates had low stream flows and also had high NH_3's, so septic systems are again suggested as a possible source.

Figure 73. Stream Nitrate plus Nitrite-N Concentration Means



Error bars are 90% confidence intervals

Figure 74. Stream Nitrate plus Nitrite-N Concentrations

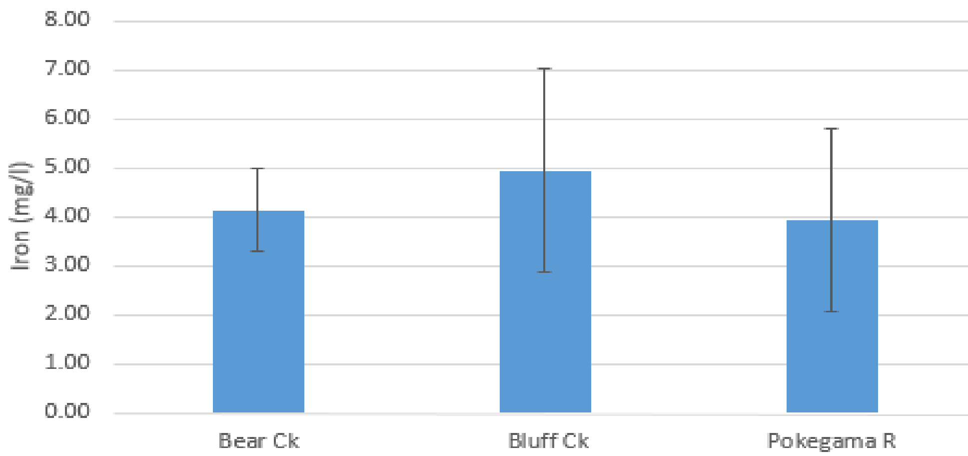


Iron

Mean iron concentrations ranged from 3.9 mg/l (Pokegama River) to 4.9 mg/l (Bluff Creek) (Table 28) (only named streams were tested). There were no significant differences between site means (Figure 75). Iron concentrations were highly correlated with stream flow (Pokegama R R^2 = 0.98, Bear Ck R^2 = 0.90, Bluff Ck R^2 = 0.94). Iron concentrations were also highly correlated with total suspended solids concentrations (Pokegama R R^2 = 0.98, Bear Ck R^2 = 0.83, Bluff Ck R^2 = 0.89). This suggests most iron was derived from soil erosion. Iron as a percent of total suspended solids ranged from 4 to 28%. Red clay contains iron, which produces its red color.

Bluff Creek was observed to be unusually red on September 20th following a ¾ inch rainfall (Figure 77). The iron concentration was 10 mg/l. The railyard for the BNSF taconite storage facility drains to Bluff Creek upstream of the sampling site and was the likely source of the color. The railyard is mostly covered with a layer of spilled taconite pellets. The color observed in Bluff Creek was nearly identical to that observed in runoff puddles within the taconite storage facility (Figure 78). Runoff from the taconite storage facility is captured and treated and does not drain to Bluff Creek.

Figure 75. Stream Iron Concentration Means



Error bars are 90% confidence intervals

Figure 76. Stream Iron Concentrations

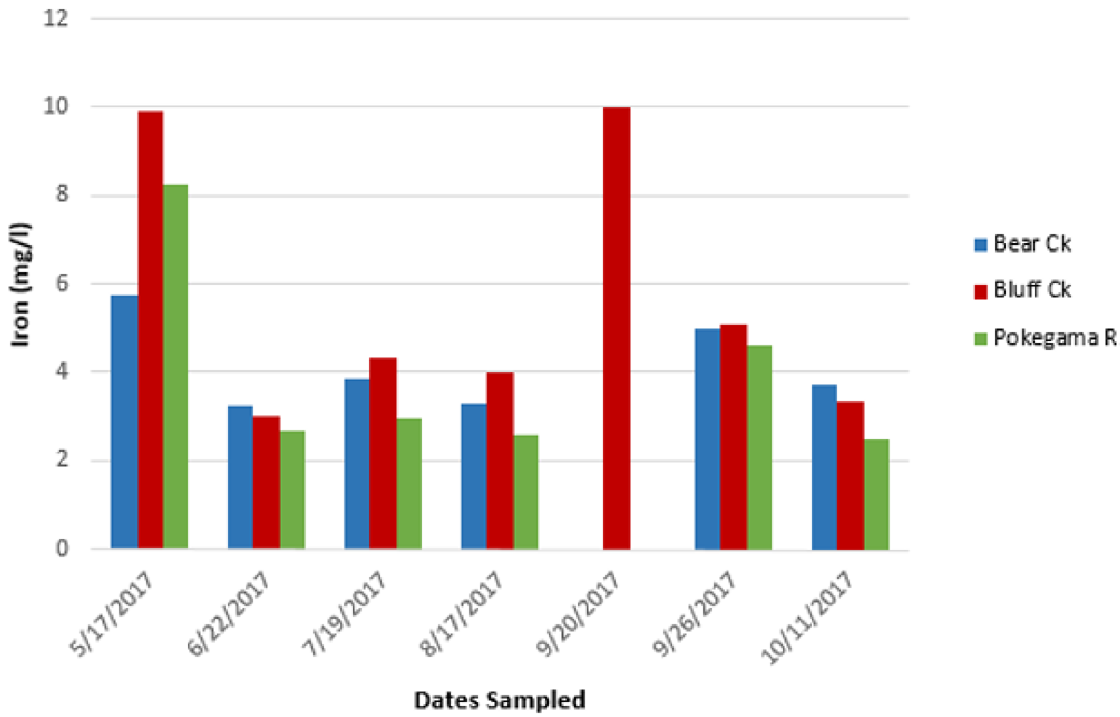


Figure 77. Red water in Bluff Creek on 9/20/17 when Iron Concentration was 10 mg/l

Figure 78. Air Photo of Runoff Puddles at BNSF Taconite Storage Facility

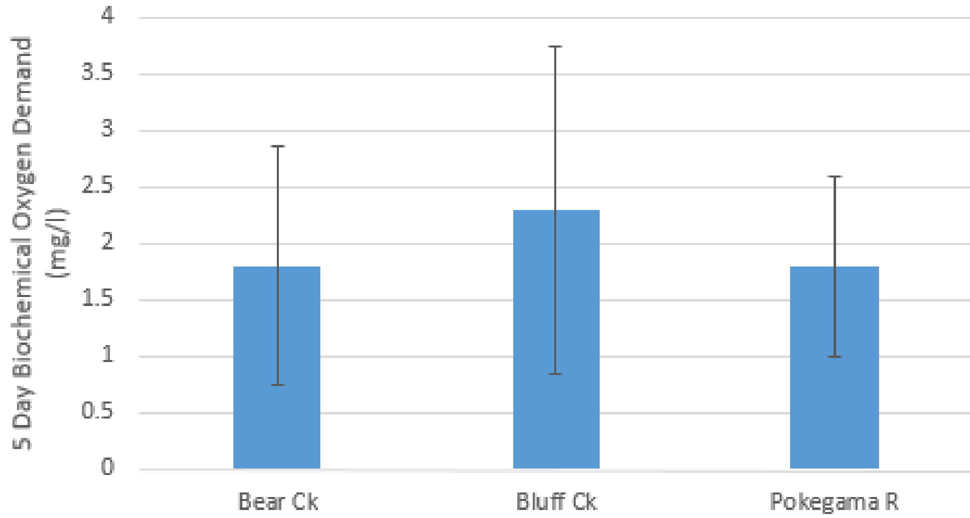
5-Day Biochemical Oxygen Demand

Mean 5-Day Biochemical Oxygen Demand concentrations (BOD's) ranged from 1.8 mg/l (Bear Creek and Pokegama River) to 2.3 mg/l (Bluff Creek) (Table 28) (only named streams were tested). There were no significant differences between site means (Figure 79). BOD's were poorly correlated with stream flow (Pokegama R R^2 = 0.23, Bear Ck R^2 = 0.008, Bluff Ck R^2 = 0.10).

BOD's were highest on June 29th and September 26th. Both days have moderate stream flow spikes (Figure 57).

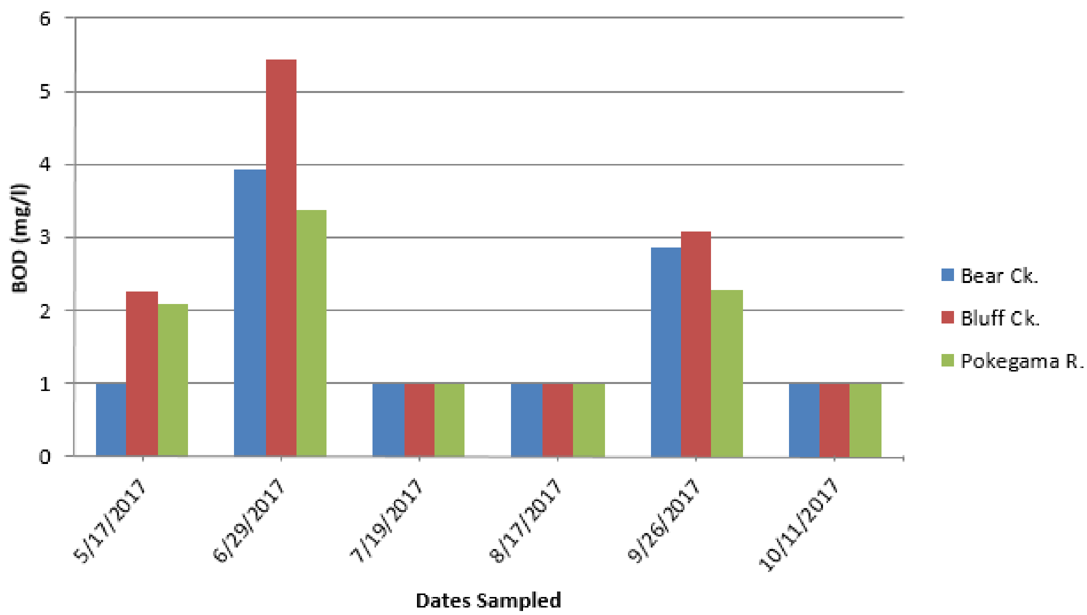
The 2017 May-October BOD load for the Pokegama River was 34,507 kg. The Village of Superior wastewater lagoons discharged 961.4 kg of BOD to the river during that period. The discharge was about 2.8 % of the river's BOD load.

Figure 79. Stream 5-Day Biochemical Oxygen Demand Concentration Means



Error bars are 90% confidence intervals

Figure 80. Stream 5-Day Biochemical Oxygen Demand Concentrations



Level of detection = 2 mg/l; samples less than LOD assumed to be 1 mg/l

Bay Sediment Characteristics

Bay sediment chemistry and grain size data is shown in table 30.

Table 30. Bay Sediment Chemistry and Grain Size

	Site	Solids	Total Organic C	Iron	Phosphorus	TKN	NH3	NO3+NO2	Sand	Silt	Clay
		%	(ug/g)	(mg/kg)	(mg/kg)	(mg/kg)	mg/kg	mg/kg	%	%	%
	ASD	24.9	50310	39000	791	3480	25.9	<1.04	4	35	61
	ASE	33	35200	15200	360	2210	0.626	<0.763	64	13	23
	ANW	33	35420	35300	765	1660	0.694	<0.748	10	45	45
Allouez Bay	AIS-1	52.4	18240	12000	190	941	0.988	<0.489	85	4	12
	AIS-2	26.4	51630	38500	789	3680	1.17	<0.930	11	34	56
	AIS-3	56.1	15780	26200	509	989	0.325	<0.451	61	14	26
	AIS-4	32.5	38240	33000	671	2210	0.777	<0.796	23	30	48
	AIS-5	31	44530	34700	775	2750	0.824	<0.792	13	42	46
Mean:		36.2	36169	29238	606	2240	3.9		34	27	40
Median:		32.8	36830	33850	718	2210	0.8		18	32	46
Min:		24.9	15780	12000	190	941	0.325		4	4	12
Max:		56.1	51630	39000	791	3680	25.9		85	45	61
	KND	35.1	32030	30200	775	1770	2.23	<0.694	16	51	33
Kimballs Bay	KND-DUP.	35.9	33220	29300	755	1880	3.46	<0.693	18	51	31
	KND-AV.	35.5	32625	29750	765	1825	2.845	<0.694	17	51	32
	KIS-1	24	38130	41100	799	2100	18.7	<1.06	6	31	63
	KIS-2	32.6	43420	32000	677	2590	4.93	<0.770	14	43	43
Mean:		30.7	38058	34283	747	2172	8.8		12	42	46
Median:		32.6	38130	32000	765	2100	4.9		14	43	43
Min:		24	32625	29750	677	1825	2.8		6	31	32
Max:		35.5	43420	41100	799	2590	18.7		17	51	63
	Site	Solids	Total Organic C	Iron	Phosphorus	TKN	NH3	NO3+NO2	Sand	Silt	Clay
		%	(ug/g)	(mg/kg)	(mg/kg)	(mg/kg)	mg/kg	mg/kg	%	%	%
	PND	31.5	21590	39600	763	1460	0.854	<0.806	5	34	62
	PMID	42.8	18820	32300	620	1390	3.07	<0.565	4	49	47
	PMID-DUP.	41.8	23150	31700	633	1150	5.18	<0.576	4	47	49
	PMID-AV.	42.3	20985	32000	626.5	1270	4.125	<0.570	4	48	48
Pokegama Bay	PS	44	20770	30500	643	1140	3.56	<0.560	7	44	50
	PIS-1	38.5	29080	31700	737	1720	0.754	<0.618	7	56	38
	PIS-2	34.3	19480	38900	721	1220	1.88	<0.711	11	46	34
	PIS-3	32	19820	40500	710	1540	3.9	<0.775	7	47	45
	PIS-4	40.1	18290	30900	611	1370	0.714	<0.617	7	54	40
	PIS-5	55.7	15840	24900	501	737	1.75	<0.445	43	22	36
Mean:		39.8	20732	33625	664	1307	2.19		11	44	44
Median:		39.3	20295	31850	677	1320	1.82		7	47	43
Min:		31.5	15840	24900	501	737	0.714		4	22	34
Max:		55.7	29080	40500	763	1720	4.125		43	56	62

Clay content of sediment (% Clay) was moderately well correlated with phosphorus concentration (R^2 = 0.75) and iron concentration (R^2 = 0.76). Iron will readily attach to the extensive bonding surfaces of clay particles, and phosphorus will attach to the iron.

Clay content was also moderately inversely correlated with % solids (R^2 = 0.43). Clay sediment tends to have a higher water content than coarser grained sediment.

Mean clay content of sediment in all three bays (40 – 46%) was significantly higher than that found in the remainder of the central and lower SLRE, where clay content averaged about 14.7% (NOAA DIVER 2018). This is not surprising given the clay rich soils in the direct watersheds of the bays.
Total organic carbon (TOC) and total Kjeldahl nitrogen (TKN) were highly correlated (R^2 = 0.92). Both parameters reflect the organic matter content of the sediment.

Allouez Bay sites had the highest mean, median and maximum % sand. There was an inverse correlation between site depth and % sand for the bay (R^2 = 0.73). Sediment scouring by wave action is probably removing finer sediments at shallow sites and leaving more sand. Proximity to sand sources may also be significant. The two sites with the highest % sand (ASE, AIS-1) are near the sandy barrier beach on the north side of the bay. The site with the third highest % sand (AIS-3) is near the mouth of Bluff Creek, where a bed load of sand is likely to enter the bay.

The Pokegama Bay sites had significantly lower TOC and TKN concentrations than the other two bays. This was probably due to the higher rates of inorganic sediment deposition due to the high watershed to bay area ratio (Table 6).

Sediment descriptions and soft sediment thicknesses are shown in Table 31. Soft sediment thickness ranged from 0.9 to 12.9 feet. For all sites, water depth and soft sediment thickness were weakly correlated (R^2 = 0.29). Deeper sites tend to favor long term sediment deposition. Site ASD in Allouez Bay was historically dredged, so the soft sediment thickness there has been altered. Water depth and soft sediment thickness showed better correlations for individual bays (Allouez Bay (less site ASD), R^2 = 0.42; Pokegama Bay, R^2 = 0.70).

Table 31. Bay Sediment Descriptions and Thicknesses

SITE	Water Depth (ft)	Soft Sediment Thickness (ft)	Sediment Description
ASD	17.5	9.5	reddish brown silt
ASE	6.7	6.4	brown silty sand with organic matter
ANW	8.2	4.6	reddish brown silt
AIS-1	5.1	0.9	reddish brown silty sand; sand beneath soft sediment
AIS-2	8.3	7.7	reddish brown silt; hard clay beneath soft sediment
AIS-3	6.9	2.1	reddish brown clayey silt with zebra mussel shells
AIS-4	7.7	1.5	reddish brown silt; sand beneath soft sediment
AIS-5	7.6	10.2	reddish brown silt; woody debris felt while probing
KND	15.8	12.7	medium brown silt
KIS-1	15.8	10	medium brown silt
KIS-2	11.8	5.1	medium brown silt with organic debris; thin sand layer penetrated 2 ft above firm bottom
PND	11	12.9	medium brown to reddish brown silt; sand layer penetrated a few feet above firm bottom
PMID	6.1	5.4	reddish brown silt
PS	3.4	5.2	reddish brown silt
PIS-1	9	9.9	medium brown silt
PIS-2	9.3	11.6	medium brown to reddish brown silt
PIS-3	11.5	10.7	reddish brown silt
PIS-4	4.9	7.1	reddish brown silt
PIS-5	4.2	8.8	reddish brown sandy clay with organic detritus

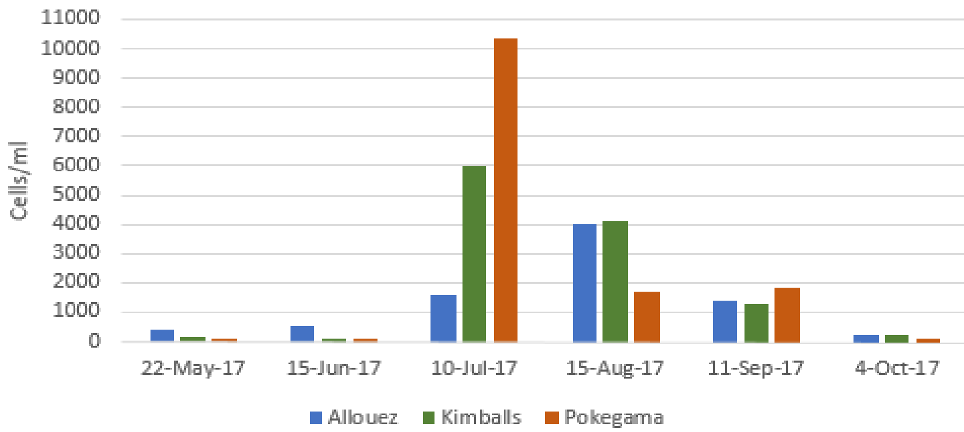
Algae

Identification and enumeration results from monthly algae samples are contained in Appendix 4. Seven phyla and 198 taxa of algae were identified.

All phyla occurred in higher densities in July, August, and September. Correspondingly, chlorophyll a concentrations were also generally higher during these months (Figure 27). Total suspended solids concentrations and turbidity were lower during these months (Figures 47 and 53) which increased light availability for algal growth. Water temperatures were higher during these months (Table 7) which can also promote algal growth.

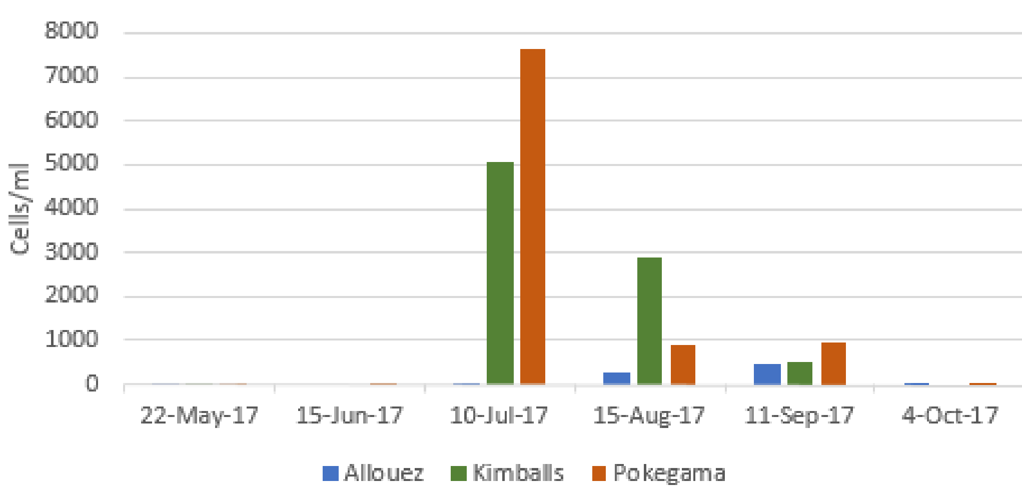
Total algal cell densities were highest in all bays in July, August, and September (Figure 81). Pokegama Bay had the highest total cell density on July 10th (10,343 cells/ml).

Figure 81. Bay Mean Total Algal Cell Densities



Blue-green algae cell densities were highest in all bays in July, August, or September (Figure 82). Pokegama Bay had the highest blue-green algae density on July 10th (7,657 cells/ml). Blue-green algae density was very low in all bays during May, June, and October (< 50 cells/ml). Allouez Bay had the lowest blue-green algae densities on five of the six sampling dates. *Aphanazomenon flos-aquae* was the dominant blue-green algae in ten of the thirteen samples with densities > 500 cells/ml.

Figure 82. Bay Mean Blue-green Algae Cell Density

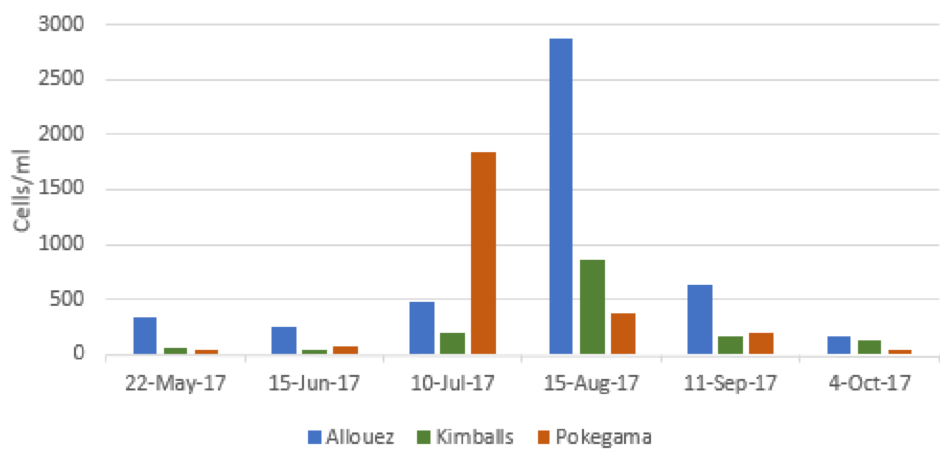


Diatom densities were highest in all bays in July or August (Figure 83). Allouez Bay had the highest diatom density on August 15th (2,875 cells/ml). Allouez Bay had the highest diatom densities on five of the six sampling dates.

Diatoms comprised > 50% of the algal population at most sites during May, June, and October, when total algal cell densities were low. They also comprised > 50% of the algal population at some sites in Allouez Bay during July, August, and September.

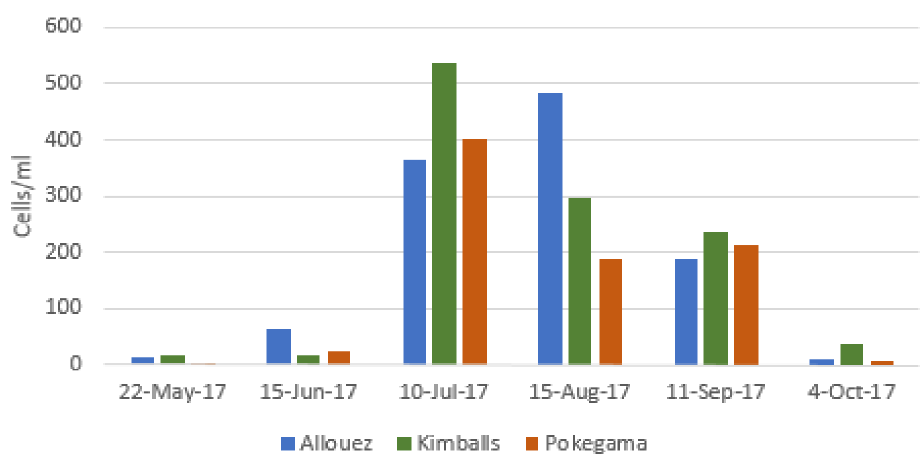
The five most abundant diatom species, in order of abundance, were – *Aulacoseira granulata*, *A. ambigua*, *A. distans*, *A. subarctica*, and *Stephanodiscus oregonicus*. The two most abundant species, *Aulacoseira granulata* and *A. ambigua,* were identified as some of the most common species in the sediment cores collected in Allouez and Pokegama Bays (Reavie 2016).

Figure 83. Bay Mean Diatom Cell Densities



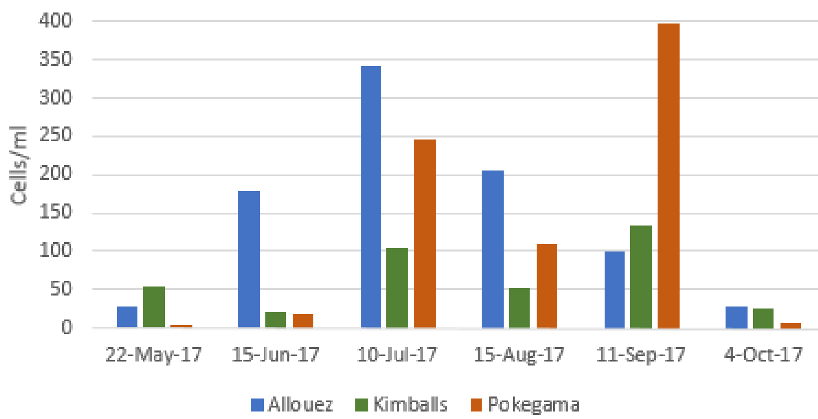
Green algae densities were highest in all bays in July or August (Figure 84). Kimballs Bay had the highest green algae density on July 10th (537 cells/ml).

Figure 84. Bay Mean Green Algae Cell Densities



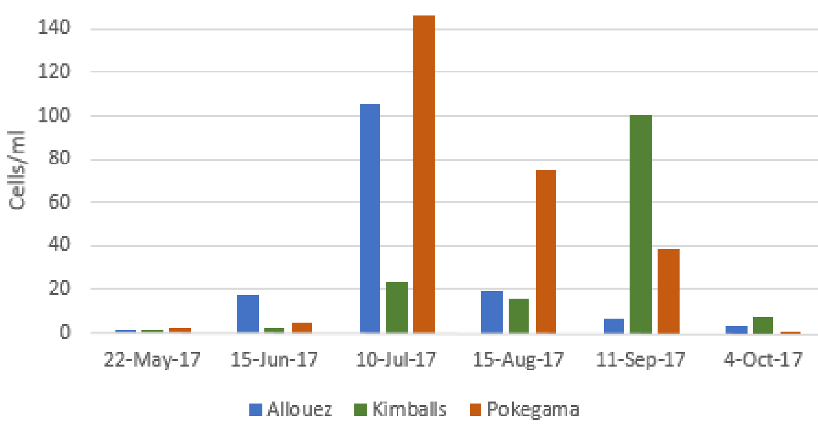
Cryptomonad densities were highest in all bays in July or September (Figure 85). Pokegama Bay had the highest Crypromonad density on September 11th (397 cells/ml).

Figure 85. Bay Mean Cryptomonad Cell Densities



Euglenoid densities were highest in all bays in July or September (Figure 86). Pokegama Bay had the highest Euglenoid density on July 10th (147 cells/ml).

Figure 86. Bay Mean Euglenoid Cell Densities



Yellow-brown algae (Chrysophyta) and dinoflagellates (Pyrrophyta) comprised small components of the algal community with monthly mean densities for all bays < 100 cells/ml.

Four of the phyla present were heterotrophic algae (Cryptomonads, Euglenoids, Chrysophytes, Pyrrhophytes). Heterotrophic algae can also consume bacteria as a food source. These algae were present at higher densities than commonly found (Pillsbury 2018). The mean heterotrophic algae cell counts for all sites comprised more than 10% of total cell counts on all dates and reached 32% for the June 15th samples. Light limitation due to clay turbidity may favor a larger heterotrophic algae population.

Benthic Invertebrates

Benthic invertebrate results from the 19 sites sampled are summarized in Table 32. Complete benthic invertebrate data is contained in appendix 6. The trimetric index (TMI) and the ephemerid (mayfly) density index developed by Angradi et al (2016) for the SLRE were applied to provide a qualitative assessment of the invertebrate communities found. The trimetric and ephemerid density indices were developed for three zones within the SLRE - Superior Bay, St. Louis Bay, and Spirit Lake. Allouez Bay and Pokegama Bay were excluded from the development of these indices since the bays were felt to have distinct water chemistry and substrate characteristics and had been infrequently sampled. Application of these indices to Allouez and Pokegama Bays is still useful since it provides a comparison to the rest of the SLRE. The indices from the SLRE zone with the most similar mean depth have been selected to apply to each bay.

Table 32. Benthic Invertebrate Trimetric and Ephemerid Density Index Values for Bay Sites

SITE	SCALED TMI	WATER DEPTH M	SUPERIOR BAY* TMI CONDITION	ST LOUIS BAY* TMI CONDITION	SPIRIT LAKE* TMI CONDITION	EPHEMERID DENSITY NO./M2	SUPERIOR BAY* EPHEMERID DENSITY CONDITION	ST LOUIS BAY* EPHEMERID DENSITY CONDITION	SPIRIT LAKE* EPHEMERID DENSITY CONDITION
KIMBALLS BAY									
KND	0.08	5.0	POOR	POOR	POOR	0	POOR	POOR	POOR
KIS-1	0.16	4.4	POOR	POOR	POOR	0	POOR	POOR	POOR
KIS-2	0.39	3.1	GOOD	FAIR	GOOD	0	POOR	POOR	POOR
BAY SITE MEAN DEPTH		4.1							
BAY MEDIAN CONDITION			POOR				POOR		
POKEGAMA BAY									
PND	0.32	3.2	FAIR	POOR	FAIR	130.4	EXCELLENT	EXCELLENT	EXCELLENT
PMID	0.40	1.6	GOOD	FAIR	POOR	434.8	EXCELLENT	EXCELLENT	EXCELLENT
PMID-DUP	0.45	1.6	GOOD	FAIR	FAIR	434.8	EXCELLENT	EXCELLENT	EXCELLENT
PS	0.44	1.1	GOOD	FAIR	FAIR	347.8	EXCELLENT	EXCELLENT	EXCELLENT
PS-1	0.43	2.6	GOOD	FAIR	GOOD	347.8	EXCELLENT	EXCELLENT	EXCELLENT
PS-2	0.32	2.6	FAIR	POOR	POOR	173.9	EXCELLENT	EXCELLENT	EXCELLENT
PS-3	0.19	3.2	POOR	POOR	POOR	0	POOR	POOR	POOR
PS-4	0.38	1.4	FAIR	POOR	POOR	43.5	FAIR	GOOD	FAIR
PS-5	0.54	1.1	GOOD	GOOD	GOOD	347.8	GOOD	EXCELLENT	EXCELLENT
BAY SITE MEAN DEPTH		2.1							
BAY MEDIAN CONDITION					FAIR				EXCELLENT
ALLOUEZ BAY									
ASD	0.12	5.2	POOR	POOR	POOR	0	POOR	POOR	POOR
ASE	0.51	1.8	GOOD	GOOD	GOOD	1913.1	EXCELLENT	EXCELLENT	EXCELLENT
ANW	0.19	2.4	POOR	POOR	POOR	43.5	GOOD	GOOD	GOOD
ANW-DUP	0.28	2.4	POOR	POOR	POOR	173.9	EXCELLENT	EXCELLENT	EXCELLENT
AIS-1	0.39	1.5	FAIR	POOR	POOR	130.4	GOOD	GOOD	GOOD
AIS-2	0.20	2.4	POOR	POOR	POOR	0	POOR	POOR	POOR
AIS-3	0.46	2.1	GOOD	FAIR	GOOD	695.7	EXCELLENT	EXCELLENT	EXCELLENT
AIS-4	0.42	2.2	GOOD	FAIR	FAIR	173.9	GOOD	EXCELLENT	EXCELLENT
AIS-5	0.23	2.2	POOR	POOR	POOR	87	GOOD	GOOD	GOOD
BAY SITE MEAN DEPTH		2.5							
BAY MEDIAN CONDITION				POOR				GOOD	

**mean zone depths for index development sites: Superior Bay - 5.0 m, St. Louis Bay – 2.8 m, Spirit Lake – 1.8 m. The indices from the SLRE zone with the most similar mean depth are highlighted in color in the table.*

The three deepest (≥ 4.4 m) sites (ASD, KND, KIS-1) all had poor TMI and ephemerid density conditions. Periods of anoxia probably occur at these sites, which limits the invertebrate community. Profile data from site ASD suggests occasional anoxia occurred (see bay water quality discussion section). Profile data from site KND indicated extended periods of anoxia occurred, and it seems likely this is the case for site KIS-1, as well.

The shallowest site in Kimballs Bay had a good TMI condition and a poor ephemerid density condition (No ephemerids were present). The median TMI condition for the bay was poor. The median ephemerid density condition for the bay was also poor. The occurrence of anoxia at two of the three sites sampled in the bay probably accounted for this.

Pokegama Bay TMI conditions ranged from poor to good. The median TMI condition for the bay was fair. Pokegama Bay ephemerid density conditions ranged from poor to excellent. The median ephemerid density condition for the bay was excellent. Allouez Bay TMI conditions ranged from poor to good. Six of the nine samples (including duplicate) were poor, two were fair, and one was good. The median TMI condition for the bay was poor. Allouez Bay ephemerid density conditions ranged from poor to excellent. The median ephemerid density condition for the bay was good.

Both Pokegama and Allouez Bay had higher total suspended solids concentrations and turbidity, and probably higher rates of inorganic sediment deposition than the remainder of the SLRE where the TMI and ephemerid density condition indices were developed. Clay content of sediment in all three bays was also substantially higher than in the remainder of the SLRE (NOAA DIVER 2018). The bay water quality along with the physical characteristics of sediment with high clay content (and corresponding high water content) may be restrictive to some benthic invertebrates and result in poorer TMI conditions. Ephemerid mayflies do not appear to be affected by these water and sediment characteristics.

Aquatic Macrophytes

Aquatic vegetation data from the St. Louis River Estuary Vegetation Database (Danz et al. 2017) was reviewed for each of the bays to assess their plant communities. Data includes several different projects over a span of eleven years (2004-2015) within the St. Louis River Estuary. Emergent, submergent, and floating leaf vegetation are included in the database. Number of species, average species per plot, and average mean Coefficient of Conservatism (mean C) were calculated from the database by project.

Mean C has a range of 0 to 10, ten being the highest quality sites with species that have a low tolerance of disturbance and are restricted to certain plant communities. Conversely, a mean C value of 0 indicates a site with species that are very tolerant of disturbance and found in a wide variety of community types. Project values were averaged for each bay and are summarized in Table 33. Species lists for the bays are contained in appendix 7.

Table 33. Aquatic Macrophyte Survey Data for Bays

	Allouez Bay	Kimballs Bay	Pokegama Bay	All SLRE surveys
Number of species	155	74	148	NC**
Species per plot	8.8	5.0	5.8	NC**
Mean C* value	5.6	3.6	5.4	5.06

*C = coefficient of conservatism, an index of tolerance to disturbance. **NC = not comparable; number of species and species per plot are influenced by size of area surveyed and survey methods, so do not offer a simple means of comparison.

Wetland vegetation data for the three bays from the Great Lakes Coastal Wetland Monitoring Program (Brady 2018) was also reviewed. Data is from surveys conducted during 2011 through 2017. IBI (index of biotic integrity) scores and ratings for the three bays were compared to survey sites that are not clay influenced. This is summarized in Table 34.

Table 34. Wetland Vegetation Biological Community Indicator Summary for Bays

BIOLOGICAL COMMUNITY	INDICATOR	ALLOUEZ BAY	KIMBALLS BAY	POKEGAMA BAY
Wetland Vegetation	Wetland vegetation IBI[1]	2011-2017 median = moderately impacted = median for non-clay influenced SLRE surveys	2014, 2016 = moderately degraded, which is poorer than the median for non-clay influenced SLRE surveys (moderately impacted).	2011, 2012, 2016 median = moderately impacted = median for non-clay influenced SLRE surveys

[1]Uzarski, DG, et al. 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands (37:15).

Allouez Bay

Allouez Bay had 155 plant species reported, the highest of the three bays. Two species of special concern, *Nuphar advena,* yellow water lily, and *Schoenoplectus torreyi,* Torrey's bulrush, were found. The bay had the highest average species per plot at 8.8, and the highest mean C value per plot at 5.6. This mean C value indicates that species tolerate moderate disturbance. It is better than the mean C value of 5.1 for all SLRE aquatic vegetation surveys.

Eight wetland vegetation surveys from Allouez Bay had a median IBI score of 2.7 (rating = moderately impacted). This IBI score is slightly poorer than, the median IBI score of 2.85 for 16 site surveys in SLRE locations that are not clay influenced. However, the median IBI rating for the Allouez Bay surveys was the same as the median rating for the 16 site surveys in SLRE locations that are not clay influenced (rating = moderately impacted).

Kimballs Bay

Kimballs Bay had the lowest number of species, with 74 plant species reported, and an average species per plot of 5.0. Mean C value was 3.6, the lowest value for the three bays. This value indicates a plant community of generalists that are tolerant of disturbance. This is substantially poorer than the mean C value of 5.1 for all SLRE aquatic vegetation surveys. Only three projects in the SLRE vegetation database had data for Kimball's Bay, which may have influenced these numbers.

Two wetland vegetation surveys from Kimballs Bay had a median IBI score of 2.05 (rating = moderately degraded). This is substantially poorer than the median IBI score of 2.85 (rating = moderately impacted) for 16 site surveys in SLRE locations that are not clay influenced.

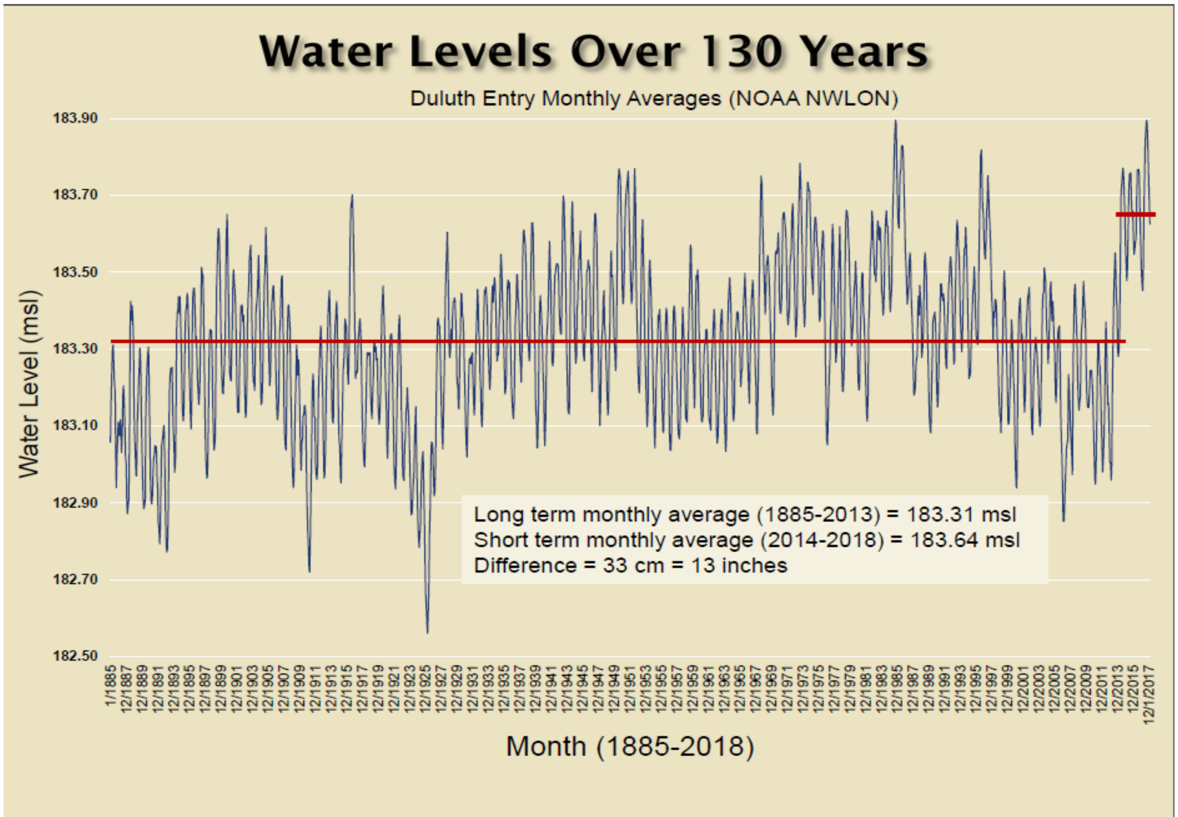
Pokegama Bay

Pokegama Bay had 148 species reported. This includes one species of special concern, *Schoenoplectus torreyi*, Torrey's bulrush. Average species per plot was 5.8. Mean C value was 5.4, indicating species that tolerate moderate disturbance. This is slightly better than the mean C value of 5.1 for all SLRE aquatic vegetation surveys.

Three wetland vegetation surveys from Pokegama Bay had a median IBI score of 2.8 (rating = moderately impacted). This is very similar to the median IBI score of 2.85 (rating = moderately impacted) for 16 site surveys in SLRE locations that are not clay influenced.

With the recent rise in Lake Superior's water level (Figure 87), a shift in Pokegama Bay's vegetation community from more emergent wetland plants to more submergent aquatic plants has been observed (Schooler 2018). Similar shifts are likely to have occurred in the other bays. Shoreward shifts of emergent plant zone boundaries and die-off of speckled alders due to rising water levels have been observed elsewhere in the SLRE (Roesler 2017).

Figure 87. Monthly Average Water Levels at the Duluth Entry of the St. Louis River (Schooler 2018)

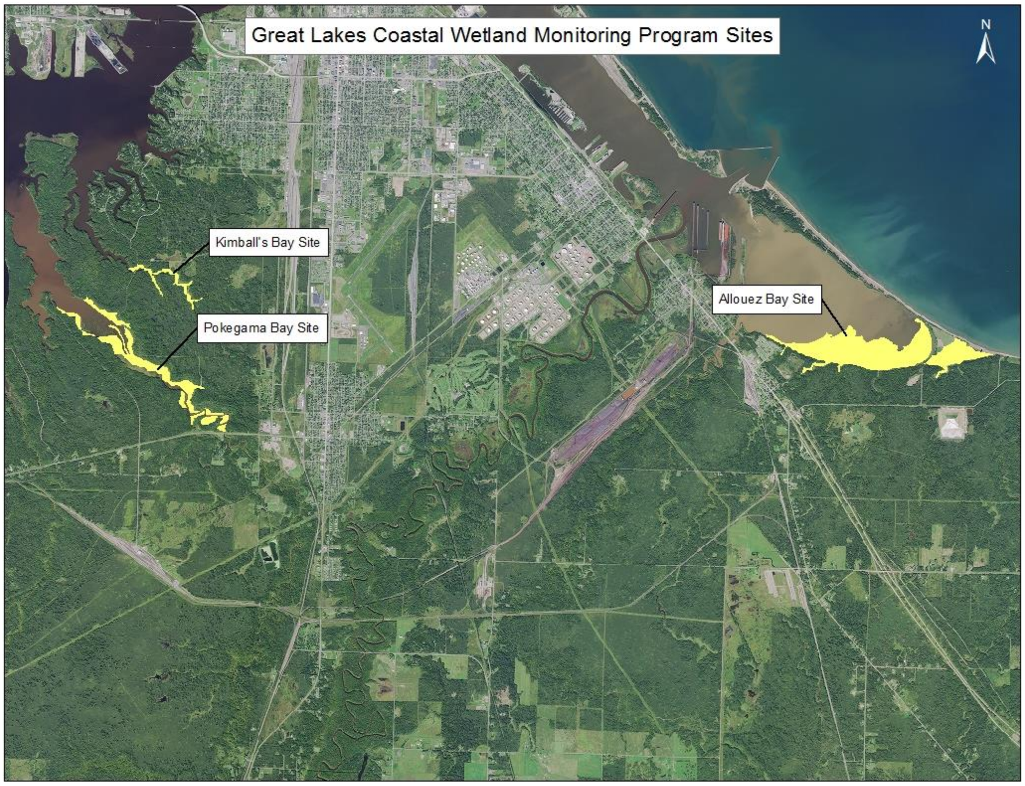


Wetlands

Wetland Data Sources

The Great Lakes Coastal Wetland Monitoring Program monitored several sites in the St. Louis River Estuary. Three monitored sites are in the bays of this study: one at the upstream end of Kimball's Bay, one in the upstream end of Pokegama Bay, and one covering most of the wetlands in Allouez Bay (Figure 88). A suite of data was collected in these wetlands during 2011-2017, including vegetation, water quality, macroinvertebrates, and fish (http://www.greatlakeswetlands.org/Home.vbhtml). A full list of parameters and protocols for this monitoring program are available in Uzarski 2016. Vegetation data from the wetland monitoring program is included in the SLRE Aquatic Vegetation Database (Danz et al. 2017) and is summarized with other aquatic plant monitoring data for the clay-influenced bays in the preceding "Aquatic Macrophytes" section.

Figure 88. Coastal Wetland Monitoring Program Sites in Study Bays



Wetland Water Quality Data

Wetland water quality data for the three bays is summarized with mean parameter values in Table 35. Allouez Bay had the lowest total phosphorus concentration (TP) (67 ug/l), the lowest total nitrogen concentration (TN) (0.709 mg/l), and the highest chlorophyll a concentration (CHL) (5.4 ug/l). Kimball's Bay had the highest TP (126 ug/l), the lowest turbidity (13.8 NTU) and lowest CHL (2.9 ppb). Pokegama Bay had the highest TN (1.16 ppm) and the highest turbidity (36.2 NTU). Mean concentrations for the four parameters were generally within the range of open water values found at nearby sites in the respective bays in July and August of 2017 (Table 36). One exception was Kimballs Bay where the wetland mean CHL was lower than the range of open water bay values. Also, the wetland mean TP was about double that found at the open water site. The CHL difference may be due to annual variability. The TP difference again suggests wetland phosphorus release is occurring in Kimballs Bay.

Dissolved oxygen concentrations (D.O.'s) were measured at the wetland monitoring sites in areas with submergent vegetation and areas with emergent vegetation. Daytime D.O.'s were less than 5 mg/l for a significant percentage of measurements (24% - Allouez Bay, 14% - Pokegama Bay, 83% - Kimballs Bay). Daytime D.O.'s were also less than 3 mg/l for a significant percentage of measurements (12% - Allouez Bay, 5% - Pokegama Bay, 25% - Kimballs Bay). Nighttime D.O.'s would be lower, and sediment surface D. O's at night may be low enough to allow sediment phosphorus release to occur at times. Kimballs Bay has the highest frequency of low daytime D.O.'s, which again suggests higher rates of sediment or wetland phosphorus release.

Table 35. Mean Water Quality Values for All Vegetation Zones from Coastal Wetland Monitoring Data (data collected during July or August of 2011 – 2017; years with data varies between bays)

Site	Turbidity (ntu)	Chlorophyll a (ug/l)	Total Phosphorus (ug/l)	Total Nitrogen (mg/l)
Allouez Bay	31.2	5.4	67	0.709
Kimball's Bay	13.8	2.9	126	0.929
Pokegama Bay	36.2	5.1	112	1.160

Table 36. Ranges of July and August 2017 Water Quality Values for Open Water Bay Site(s) Closest to Wetland Monitoring Zones.

Site	Turbidity (ntu)	Chlorophyll a (ug/l)	Total Phosphorus (ug/l)	Total Nitrogen (mg/l)
Allouez Bay (site ASE)	28 - 58	2.7 - 15.5	46 - 82	0.72 - 0.84
Kimball's Bay (site KND)	9 - 13	7.7 - 20.7	56 - 63	0.85 - 1.01
Pokegama Bay (sites PS and PMID)	32 - 123	2.7 - 23.4	77 - 156	1.0 - 1.6

Wetland Macroinvertebrates

Allouez Bay wetlands had the highest macroinvertebrate taxa richness with 88 taxa found. Kimball's Bay had the lowest macroinvertebrate taxa richness with 54 taxa found. Pokegama Bay had 77 macroinvertebrate taxa found. Wetland macroinvertebrate IBIs were available for Allouez Bay and Pokegama Bay and are summarized in Table 37.

Table 37. Wetland Macroinvertebrate Biological Community Indicators

BIOLOGICAL COMMUNITY	INDICATOR	ALLOUEZ BAY	KIMBALLS BAY	POKEGAMA BAY
Wetland Macroinvertebrates	Wetland macroinvertebrate IBI[1]	2011, 2012 = moderately impacted; not enough non-clay influenced SLRE surveys to allow comparison.	IBI not available	2011, 2012 median = mildly impacted; not enough non-clay influenced SLRE surveys to allow comparison.
[1]Uzarski, DG, et al. 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands (37:15).				

Allouez Bay had a score of 134 in 2011 and 130 in 2012. Both scores are considered moderately impacted. Pokegama Bay had a score of 136 in 2011, which is rated as moderately impacted, and a score of 162 in 2012, which is considered a reference condition or most pristine. There were not enough SLRE survey sites from locations not influenced by clay to allow a comparison.

Wetland Birds and Frogs

Wetland bird and frog survey results (2012-2013) are available for Allouez and Pokegama Bays (Tozer 2014). Additional wetland bird and frog survey result are available for one or more years during 2014 -2017 for all three bays (Brady 2018). The 2014-17 survey results are compared to survey results from SLRE survey sites not influenced by clay turbidity. Results from both data sets are summarized in Table 38.

Table 38. Wetland Bird and Frog Biological Community Indicators

BIOLOGICAL COMMUNITY	INDICATOR	ALLOUEZ BAY	KIMBALLS BAY	POKEGAMA BAY
Wetland Birds	Bird IBI[1]	2012-13 IBI = 31.8; fair - slightly poorer than the median value of 33.3 found for 14 Lake Superior coastal wetlands, mostly	no data	2012-13 IBI = 34.0; fair - slightly better than the median value of 33.3 found for 14 Lake Superior coastal wetlands, mostly outside of SLRE
Wetland Birds	Bird IEC[2]	2014 2016, 2017 median = high quality, which is better than the median for non-clay influenced SLRE surveys (moderately impacted)	2016 = degraded, which is poorer than the median for non-clay influenced SLRE surveys (moderately impacted)	2016 = mildly impacted, which is better than the median for non-clay influenced SLRE surveys (moderately impacted)
Wetland Frogs	Frog IBI[1]	2012-13 IBI = 60.0; good - poorer than the median value of 86.5 found for 13 Lake Superior coastal wetlands, mostly outside of SLRE	no data	2012-13 IBI = 70.3; very good - poorer than the median value of 86.5 found for 13 Lake Superior coastal wetlands, mostly outside of SLRE
Wetland Frogs	Frog IEC[2]	2014 2016, 2017 median = reference condition, which is better than the median for non-clay influenced SLRE surveys (mildly impacted)	2016 = moderately degraded, which is poorer than the median for non-clay influenced SLRE surveys (mildly impacted)	2016 = moderately impacted, which is poorer than the median for non-clay influenced SLRE surveys (mildly impacted)
[1]Tozer, D. 2014. LSRI nearshore monitoring project: 2012-2013 bird and frog indices of biotic integrity. EPA assistance no. GL00E00500-0.				
[2]Uzarski, DG, et al. 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands (37:15).				

For the 2012-13 bird surveys, Allouez Bay had an index of biotic integrity (IBI) score of 31.8 (rated fair) which is slightly poorer than the median score of 33.3 found for 14 Lake Superior coastal wetlands (mostly outside of the SLRE). Pokegama Bay had a score of 34.0 (rated fair) which is slightly better than that median score. For Allouez Bay, three wetland bird surveys (2014,2016,2017) had a median index of ecological condition (IEC) rating of high quality, which is better than the median for SLRE survey sites in locations not influenced by clay (moderately impacted). A Kimballs Bay survey (2016) had an IEC rating of degraded, which is poorer than the median for SLRE survey sites in locations not influenced by clay. A Pokegama Bay survey (2016) had an IEC of mildly impacted, which is better than the median for SLRE survey sites in locations not influenced by clay.

For the 2012-13 frog surveys, Allouez Bay had an IBI score of 60.0 (rated good) which is poorer the median score of 86.5 found for 13 Lake Superior coastal wetlands (mostly outside of the SLRE). Pokegama Bay had a score of 70.3 (rated very good) which is also poorer than that median score.
For Allouez Bay, three wetland frog surveys (2014,2016,2017) had a median IEC rating of reference condition, which is better than the median for SLRE survey sites in locations not influenced by clay (mildly impacted). A Kimballs Bay survey (2016) had an IEC rating of moderately degraded, which is poorer than the median for SLRE survey sites in locations not influenced by clay. A Pokegama Bay survey (2016) had an

EIC rating of moderately impacted, which is poorer than the median for SLRE survey sites in locations not influenced by clay.

Wetland Fish

Allouez Bay had 33 species of fish captured (Table 40) and of those 6 were invasive species: alewife, common carp, Eurasian ruffe, tubenose goby, round goby, and white perch. Kimballs Bay had the lowest number of fish species captured, 17, (Table 41) two of which were invasive (Eurasian ruffe and tubenose goby). Pokegama Bay had 19 fish species captured (Table 42) with two species being invasive (common carp and Eurasian ruffe). The more common species found in each bay's wetlands are listed in Table 39. More surveys were done in Allouez Bay, which may partially account for the larger number of common species found there.

Allouez Bay has site level wetland fish IBI's available for five survey years. The IBI ratings range from moderately degraded (2011, 2013, 2015) to mildly impacted (2016). Kimballs Bay has an IBI rating of moderately degraded for a single 2014 survey. Pokegama Bay has an IBI rating of mildly impacted from a single 2012 survey.

Table 39. Common Wetland Fish Species Found

	Fish species with vegetation zone average CPUE's >10
Allouez Bay	
2011,2013,2015,2016,2017 surveys	
	Yellow perch, yellow perch YOY
	Central mudminnow
	Black crappie YOY
	Emerald shiner
	Spottail shiner, spottail shiner YOY
	Round goby
	Bluegill or pumpkinseed, bluegill or pumpkinseed YOY
	Golden shiner YOY
Kimballs Bay	
2014, 2016 surveys	
	Yellow perch YOY
	Golden shiner YOY
	Pumpkinseed
	Black crappie YOY
Pokegama Bay	
2011, 2012 surveys	
	Black crappie YOY
	Bluegill or pumpkinseed YOY
	Black or brown bullhead YOY
	Golden shiner, golden shiner YOY
CPUE = catch per unit effort	
YOY = young of year	

Table 40. Alllouez Bay Wetland Fish Species

(invasive species are highlighted in orange)

Common Name	Scientific Name
Alewife	Alosa pseudoharengus
Black Bullhead	Ameiurus melas
Black Crappie	Pomoxis nigromaculatus
Blacknose Shiner	Notropis heterolepis
Brook Silverside	Labidesthes sicculus
Brown Bullhead	Ameiurus nebulosus
Central Mudminnow	Umbra limi
Channel Catfish	Ictalurus punctatus
Common Carp	Cyprinus carpio
Common Shiner	Luxilus cornutus
Emerald Shiner	Notropis atherinoides
Eurasian Ruffe	Gymnocephalus cernua
Fathead Minnow	Pimephales promelas
Freshwater Drum	Aplodinotus grunniens
Tubenose Goby	Proterorhinus semilunaris
Golden Shiner	Notemigonus crysoleucas
Johnny Darter	Etheostoma nigrum
Logperch	Percina caprodes
Mimic Shiner	Notropis volucellus
Northern Pike	Esox lucius
Pumpkinseed	Lepomis gibbosus
Rock Bass	Ambloplites rupestris
Round Goby	Neogobius melanostomus
Sand Shiner	Notropis stramineus
Shorthead Redhorse	Moxostoma macrolepidotum
Silver Redhorse	Moxostoma anisurum
Smallmouth Bass	Micropterus dolomieu
Spottail Shiner	Notropis hudsonius
Tadpole Madtom	Noturus gyrinus
Trout-perch	Percopsis omiscomaycus
White Perch	Morone americana
White Sucker	Catostomus commersonii
Yellow Perch	Perca flavescens

Table 41. Kimballs Bay Wetland Fish Species

(invasive species are highlighted in orange)

Common Name	Scientific Name
Black Crappie	Pomoxis nigromaculatus
Bluegill	Lepomis macrochirus
Brown Bullhead	Ameiurus nebulosus
Eurasian Ruffe	Gymnocephalus cernua
Fathead Minnow	Pimephales promelas
Freshwater Tubenose Goby	Proterorhinus semilunaris
Golden Shiner	Notemigonus crysoleucas
Johnny Darter	Etheostoma nigrum
Largemouth Bass	Micropterus salmoides
Pumpkinseed	Lepomis gibbosus
Rock Bass	Ambloplites rupestris
Shorthead Redhorse	Moxostoma macrolepidotum
Tadpole Madtom	Noturus gyrinus
Walleye	Sander vitreus
White Sucker	Catostomus commersonii
Yellow Bullhead	Ameiurus natalis
Yellow Perch	Perca flavescens

Table 42. Pokegama Bay Wetland Fish Species

(invasive species are highlighted in orange)

Common Name	Scientific Name
Black Bullhead	Ameiurus melas
Black Crappie	Pomoxis nigromaculatus
Bluegill	Lepomis macrochirus
Brown Bullhead	Ameiurus nebulosus
Channel Catfish	Ictalurus punctatus
Common Carp	Cyprinus carpio
Emerald Shiner	Notropis atherinoides
Eurasian Ruffe	Gymnocephalus cernua
Golden Shiner	Notemigonus crysoleucas
Johnny Darter	Etheostoma nigrum
Logperch	Percina caprodes
Northern Pike	Esox lucius
Pumpkinseed	Lepomis gibbosus
Spottail Shiner	Notropis hudsonius
Tadpole Madtom	Noturus gyrinus
Trout-perch	Percopsis omiscomaycus
White Perch	Morone americana
White Sucker	Catostomus commersonii
Yellow Perch	Perca flavescens

Bay Fish Communities

A bay fish assessment was done as a companion project to the SLRE Clay-Influenced Bay Assessment project. The fish assessment project was conducted by Wisconsin DNR fish management staff. The complete project report (Nelson 2018) is available elsewhere and is summarized here.

Bay fisheries were monitored during 2017 using gill nets and shoreline electrofishing. Results are summarized and compared to Minnesota DNR 2017 gill netting results in Table 43 below:

Table 43. Bay Fish Data Summary with Comparison to MN DNR Gill Net Data

Gill Net Data	Allouez Bay	Kimballs Bay	Pokegama Bay	21 MN SLRE gill net sites
Total number of species	12	6	9	19
Median number of species/net lift	9	3	9	8
Mean fish/net lift	39.9	3.6	19.3	27.5
Mean kg fish/net lift	21.9	1.3	8.3	13.0
Gill Net plus Electrofishing Data				
Total number of species	22	15	21	not applicable
Number of native species	18	14	16	not applicable
Number of non-native species	4	1	5	not applicable
Number of intolerant species	4	4	3	not applicable

Allouez and Pokegama Bays gill net data is generally similar to data collected by the Minnesota DNR during 2017 from 21 SLRE gill net sites for median number of species/net lift, mean fish/net lift, and mean kg of fish/net lift. Kimballs Bay gill net data is substantially lower than the Minnesota DNR data for those parameters. The total number of species from the 21 Minnesota gill net sites is higher than in the three bays. Only one site in each bay was netted, so these values are not comparable.

Total number of fish species captured ranged from 15 in Kimballs Bay to 22 in Allouez Bay. One to five non-native species were found in each bay. Three to four intolerant species were found in each bay.
A list of fish species found and the catch totals for gill netting and electrofishing combined are shown in Table 44.

Fish considered at least moderately tolerant of turbid conditions made up 85% of the catch in Allouez Bay, 97% in Kimballs Bay, and 94% in Pokegama Bay. Kimballs Bay, with the highest percent turbidity tolerant fish, has substantially lower turbidity than Allouez and Pokegama Bays. Additional data from throughout the SLRE would need to be assessed to determine if there is a relationship between turbidity tolerant fish and local water turbidity.

Only one fish, a northern pike in Allouez Bay with an open lesion, was found with a visible DELT (deformities, eroded fins, lesions, or tumors). That fish accounted for 0.6% of the total catch for the bay.

Conclusions of the fishery survey report included, "Despite turbid conditions that may lead to the perception of poor water quality or habitat, locally popular sport fish species like walleye, northern pike, black crappie, and yellow perch were well represented in both Allouez and Pokegama Bays. Other species of interest to anglers and state fisheries management agencies were also found in these bays including lake sturgeon, muskellunge, bluegill, and channel catfish. While Increased turbidity in Allouez and Pokegama Bays may influence the presence or abundance of specific species, it has not diminished the fishery value or eliminated desirable gamefish species from these areas."

Table 44. Combined Gill Netting and Electrofishing Catch

	COMBINED GILL NETTING AND ELECTROFISHING CATCH BY BAY		
FISH SPECIES	ALLOUEZ	KIMBALLS	POKEGAMA
Black Crappie	10	1	8
Bluegill	0	12	9
Brown Bullhead	1	1	0
Channel Catfish	35	0	8
Common Carp	0	0	2
Emerald Shiner	7	0	1
Eurasian Ruffe	2	1	3
Freshwater Drum	4	0	1
Golden Shiner	0	14	10
Lake Sturgeon	2	0	0
Largemouth Bass	0	4	2
Log Perch	2	0	3
Mimic Shiner	4	0	0
Muskellunge	1	2	0
Northern Pike	10	5	6
Pumpkinseed	1	5	7
Rock Bass	2	1	1
Shorthead Redhorse	12	1	0
Silver Redhorse	7	0	4
Smallmouth Bass	1	1	1
Spottail Shiner	7	1	2
Walleye	20	3	16
White Bass	5	0	5
White Perch	3	0	15
White Sucker	5	0	3
Yellow Perch	37	15	18
Total individuals	178	67	125

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